DEVELOPMENT OF NATURAL LANGUAGE APPLICATION FOR CONSTRUCTION SITE PROCESSES SAFETY SUPPORT

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Abstract

Efficiency in safety management at construction sites is an extremely present issue despite the many technological advances that could represent valuable means of support. This is because safety is a complex, multifactorial field in which the human factor plays a central role. It is precisely for the latter reason that finding systems that integrate technology into processes in as natural a way as possible is a challenge to be met. In this context, this research aims to develop a Digital Twin that takes use of Natural Language Processing for supporting safety during construction site operations through communication improvement.

Introduction

Construction is a complex process that requires decisions at every stage. Decision makers are inevitably influenced by past experience, situational knowledge, and other human factors. This often results in operational inefficiencies or safety and environmental problems (Saini et al., 2022). Safety management on construction sites has always been a critical issue in the construction sector since, as is well known, among all industries this is the one with the highest number of fatal accidents even today (Mihic et al., 2019). In this context, the support that could be given by innovative technologies still fails to be incisive (Yap et al. 2022). What makes it extremely difficult to go to work on incorporating new technologies into safety management worksites is that it is a complex issue. The explanation for this lies in multiple factors (Giri, 2020):

- the construction site is a workplace that evolves (rapidly) over time.
- construction procedures are not as precisely defined as operations within factories.
- the centrality in many cases of workers in implementing safety procedures and thus the human factor (Haupts et al., 2019).
- health and safety risk assessments, especially in the drafting of safety plans, which often use standard prescriptions instead of identifying, on a site-by-site basis, the main critical issues.

All of this contributes to the fact that what happens on a construction site, including from a safety management perspective, is difficult to predict in advance and therefore needs appropriate tools. This complexity has also led over time to a misguided approach of focusing on certain types of hazards while neglecting an integrated approach (Mihic et al., 2019).

This has resulted in the paradigm recently promoted for the management of domains characterized by high complexity, namely the concept of digital twin (DT) (Saini et al., 2022). Due to the characteristics of real-time interaction and self-evolution, DT is considered the best technology that can contain all the required information (Zhao et al., 2019). One aspect that is often overlooked in DT development, however, is the circularity of information that on the one hand is collected from the real environment but on the other hand should return to it so that the agents involved can learn about the information and possibly self-correct. This approach from a safety perspective is called safety II. In order, however, to communicate the information needed for safety management on the job site, one aspect to consider is that this information be easily usable and integrated into the processes. The use of natural language represents an optimal method of communication on the construction site for the purpose of human-machine interaction that is as natural as possible. The innovation proposed in this research concerns the integration of several innovative technologies (localization using UWB and RTK sensors, natural language, BIM approach for representing the built environment) in order to develop an application to support safety in construction processes. One of the innovative aspects is the use of NLP in spoken form, as opposed to the more widely used automatic text analysis, is the communication improvement on the construction site. This together with the early detection of dangerous situations through the development of DTs represents a method to apply a safety II approach with the aim of guiding workers toward recommended attitudes rather than pursuing an exclusively prescriptive approach.

Literature review

The construction industry is recognized for its dynamic and complex nature. Safety planning in construction environments is therefore challenging. Moreover, due to the lack of standardization of production processes it is very complicate to incorporate new methods and technologies into workflows without disrupting the entire industry. Among new technologies, BIM is the most cited approach in the literature. This is usually used in conjunction with other innovative technologies or the basis for others (e.g., AR) (Khudhair et al., 2021). This is also because if BIM means IFC this represents only a part of all the knowledge underlying the processes of the construction industry, namely the objects of which a building is composed. Missing from this representation are a number of crucial parts including the representation of processes, workings, economic aspects and temporal aspects. Furthermore, in the construction industry textual information (including BIM) is the dominant data type that exists in every stage of construction management, with over 80% of it being unstructured (Shamshiri et al., 2024; Wu et al., 2022). This information format is not very convenient to use on the construction site. It is precisely this high percentage of written text in construction management that has caused much research over the years to introduce natural language as a tool for handling this amount of data. Some approaches to Natural Language Processing (NLP) involve its use for interpreting documents. In (Fang et al., 2020) they developed a novel approach for classifying text contained with safety reports specifically in the case of near misses using NLP specifically to gather information in a smart way. Similarly (Baker et al., 2020) test two state-of-the-art deep learning architectures for NLP, providing a method for identifying (after training) the textual patterns. Again, the application of NLP is focused on automation in document interpretation. (Martinez et al., 2020)'s retrieval systems have been proposed for retrieving accident cases and supporting health and safety plan preparation. (Tian et al., 2023) have developed an information retrieval system that can answer questions about the best procedures to follow regarding safety during operations. Shamshiri et al., 2024 highlight how the use of NLP applications interests' safety management much more than the other domains of interest. Despite this, most text classification and information extraction applications have been widely used for the specific task of construction site accident and injury reports.

However, one aspect lacking in safety management is communication, and so natural language voice interaction (rather than written) could be a real breakthrough in workplaces where the use of paper and digital texts is not very smooth. There are two different types of interactions that can be imagined on a construction site between human agents and a Vocal Virtual Assistant (VVA). The first one requires the user to begin an interaction (passive VVA). The second one requires the system to monitor the human and artificial agents on the construction site, and proactively sends voice commands or requests to specific human actors on the field (pro-active safety VVA).

In the present work we focus on pro-active safety VVAs because assuming that workers would actively begin an interaction with a safety VVA would be equivalent to assuming that they continuously have a high degree of awareness level for safety hazards on their working environment. Unfortunately, field experience and the vast literature on construction site risk management and hazards teach us that repetitive and tiring tasks such as those characterizing the construction industry induce the workers to lower their safety hazards awareness levels. This motivates the development of a methodology for implementing an efficient pro-active safety VVA that would either provide useful safety hints to the workers on site or ask questions that aim to raise the level of attention of the worker potentially at risk.

Methodology

In Fig. 1 a methodology is introduced for driving the integration of the required technologies (see Fig. 1). The methodology spans two of the main stages of a construction project, viz. system set up and construction phase. During system set up, the first step concerns the digital representation of agents that are relevant for safety reasons (workers, vehicles, equipment, ...). Next, a connection between the real environment and the digital environment is established and maintained along time installing and configuring a network of sensors capable of localizing the described agents in the construction site (the technology for the sensor network is chosen based on the specific construction site, and especially it depends on whether it is outdoor, indoor, or mixed). In the Natural Language Processing step, the NLP microservice of the platform is fed with a set of sentences that should be recognized or reproduced by the platform itself in order to interact with the workers when it is needed. The construction phase is divided in two main steps: construction site monitoring and interaction. The former observes the positions of the agents in the construction site and detects whether some of the rules should be activated. The latter takes care of the voice interaction with the worker following the specific rules that are activated during the monitoring step, if any.

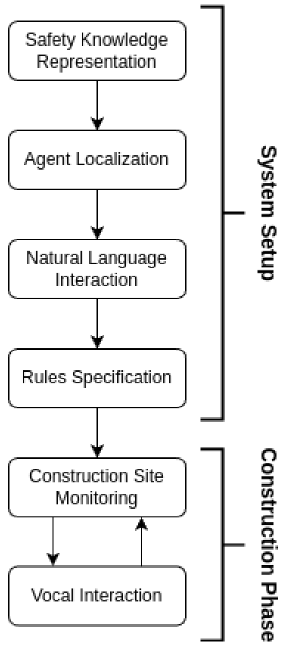

Figure 1 - Methodology

Safety knowledge digital representation

Construction site safety management is a complex issue because it requires the knowledge and integration of different information. Indeed, aspects that are part of safety concern workers, equipment, operations, hazards and spaces to name a few. Multiple efforts to represent aspects concerning safety can be found in the literature. From methods to classify hazards (Mihic et al., 2018; Fang et al., 2020; Johansen et al., 2023) to integrations with existing built classification such as IFC (Farghaly et al., 2022) contexts (Doukari et al., 2024; Gao et al., 2022) and rules (Shen et al., 2022).What is clear from these studies, however, is that to create an ontology that can collect everything that is needed for construction site safety monitoring is almost impossible.

This is because the domains to which the various parts to be taken into account refer are very different, and in the perspective of digitization of construction these differences become even more evident. In fact, if one thinks of BIM as a building model this involves a digital transposition of information based on objects, not on processes and workings that for example are central to making reasoning in the field of safety.
For this reason, the method chosen to deal with knowledge was to integrate different representations. The ontology that was taken as the basis is the one presented by (Zhang et al., 2015). Since the primary focus in this work is on monitoring resources (workers and machinery) in the chosen ontology we focused on the structure of resources not using the other parts for the time being. A handbook from the National Institute for Insurance against Accidents at Work (INAIL, 2019) was referenced to identify which components within the classification made sense to consider. This manual was compiled following the 2016 earthquake that struck central Italy. In the aftermath of that tragic event a very large number of construction sites were opened at the same time and in areas (urban centers, often including historic ones) that provided even more risks and aspects to be taken into account. In light of the great turmoil for reconstruction that is still unfinished today these guidelines identify the necessary human resources, machinery and equipment for each job. These items were used to fill within the system the categories identified by the chosen ontology.
As for the spaces that refer to the different construction site areas, we chose to model them with a BIM authoring software and then export information in IFC. The construction site layout is a mandatory document in Italy forming part of the safety documents. In this first implementation of the system, a single construction site layout was modelled with BIM and inserted into the DT platform to be used as a basis of the spatial reasoner. The site spaces planned for machine allocation, maneuvering, material storage, and different work areas were modeled in BIM as IFCSpace to identify their geometry and dimensions in digital space. In subsequent developments of the system, it could be envisaged to have more than one BIM model of the construction site with identified spaces and their changes in the duration of the construction.

Agent localization

Agents' localization on the construction site for the purpose of which the installation of a sensor network is planned. The real-time localization system has the task of attributing spatial coordinates to any entity, equipment or person, moving around the construction site.
The first requirement of the network for agent localization in order to be effectively implemented is high-precision localization capabilities in both open and closed environments for work taking place outside buildings and inside. The second one is real-time data sending to a platform for DT management.
The technologies selected for tracking are Ultra Wide Band tags for indoor and GPS-RTK for outdoor (Corneli et al., 2023). The two technologies can also be integrated into one tag which would allow both technologies to be exploited simultaneously in the case of mixed indoor/outdoor environments. As for UWB technology this involves the use of battery-powered mobile tags (to be provided to workers and attached to machinery) and requires the placement of anchors and gateways, two powered components. For this reason, UWB technology is intended for use in indoor environments where wiring the system is not an added risk to the worksite compared to outdoor environments. The accuracy for UWB localization is 10 cm.
On the other hand, for outdoor use, the technology used is GPS-RTK, which provides an accuracy of 1,5 cm. This can be implemented through an antenna inside the tags, which are provided to personnel and hooked onto the machinery. In both cases, localization information is sent by the sensor network to the Digital Twin Platform by means of intermediary service implementing a publish-subscribe information exchange pattern. This is often the case of services such as MQTT or SignalR.

Natural Language Interaction

The vocal interaction is a natural means of communication among agents in the construction site. Technological advancements in recent years make feasible to apply vocal interaction using natural language even on miniaturized and wearable devices. Cloud computing and high speed internet allows to displace the task of "reading" a given sentence or recognizing a vocal interaction on remote computers that are likely to have higher computing capabilities than those on the construction site. Neural networks allow to automatically transcribe the voice input onto its textual representation with high accuracy.
In our methodology, a pro-active safety VVA contains a collection of sentences that can be reproduced to specific group of people on the field, under suitable conditions. Each sentence is a template, mixing raw text with expressions that are computed if and when the sentence is reproduced. For instance, take the following sentence:

{{ A.name }}, you are in danger: equipment {{ B.name }} is too close!

In it {{ A.name }} and {{ B.name }} denote expressions that should be evaluated in order to deduce, respectively, the name of the worker at risk and the name of the equipment that represents a danger for the worker. A sentence with expressions in double curly braces is called an open-sentence, while sentences that do not contain expressions in curly braces are called closed-sentences. The key difference between the two kinds is that the latter can easily be converted to an audio file passing it as input of one of the several available text-to-speech AI driven cloud services, while the former need a pre-processing stage responsible for replacing the expressions with meaningful pieces of text. How this pre-processing phase happens is explained in the last stage of the methodology. The fact that sentences contain parameters allow the system to be more explicit and address specific workers calling them by name or referring to their close context.

This contributes in increasing the level of awareness in workers that perhaps do not even notice that their context is changing around them in a way that is becoming too risky to continue their task.

Parameters in template sentences are associated with one among three types of entities from the selected safety ontology: Human Resource, Equipment, or Space.

In general, the Safety Manager can devise sentences that aim to:

- raise the level of awareness in workers that are closer to dangerous or risky areas, equipment, or materials
- ask the worker for confirmation that he/she is wearing the required personal protective equipment (PPEs) or had the proper training;
- ask the worker to stay out of a delimited area.

It is evident that such goals can only be achieved by a pro-active safety VVAs.

Rules Specification

In order for the VVA to exhibit a pro-active behavior, the Digital Twin Platform must have the tools to express how to react when agent positions change, possibly denoting a risky situation on the field. To this aim, the methodology provides a stage for specifying rules that will activate the vocal interactions of the system with the workers on the field. In this stage the Safety Manager can model the configuration of agents locations that will initiate a vocal interaction of the Digital Platform, and what workers should be involved in the interaction. To this aim, each rule allows to specify two core pieces of information: a preconditions; an NLP sentence; one or more workers.

The precondition expresses under what circumstances the rule should trigger a vocal interaction (Fig. 2). The NLP

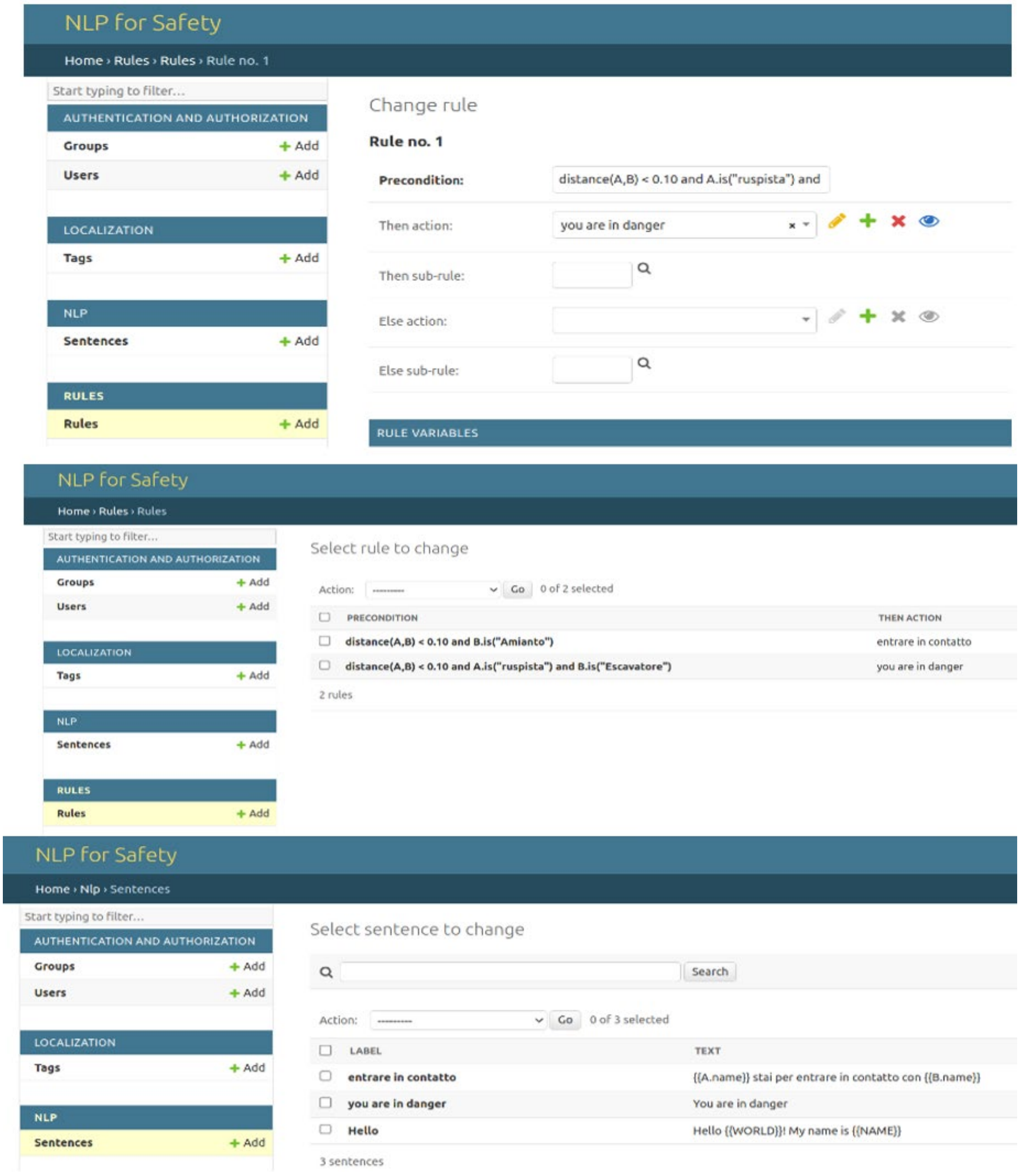

Figure 2 - NLP implementation: from above 1. rule definition; 2. rule-vocal action combination; 3. vocal action composition.

sentence specifies what audio message the Digital Twin Platform should send to the workers.

The rules preconditions are boolean formulas that can contain:

- variables;
- rational numbers;
- boolean operators (and, or, not);
- arithmetic operators (+, -, *, \);
- comparison operators among rational numbers (>, <, ==, !=); and
- function names.

From a formal point of view, the rule precondition is a first-order, existentially quantified, boolean formulas over rational numbers. An example of rule precondition is the following:

\exists A:Human Resource, \exists B: Equipment. (B.identifier == "BridgeCrane" and distance(A,B) < 0.5 and A.identifier == "BridgeCraneOperator")

The intended meaning of such a precondition is to detect when any worker qualified as a bridge crane operator is "close enough" (less than 50 cm) to the controller of the bridge crane on the construction field.

The target of the rule, i.e. the recipient of the vocal message, can be the involved worker, in case the aim of the Safety Manager is to raise the attention of the worker itself, or it can be the Safety Manager, in case she/he wants to be notified of certain relevant events happening on the construction field.

Construction Site Monitoring and Vocal Interaction

Construction Site Monitoring constitutes of a digital process continuously receiving updates concerning the agents locations on the field, and at each location update all the rule preconditions in search for those rules that should be considered enabled.

In order to detect that a rule is enabled, the Construction Site Monitoring contains a pattern matching logic searching for agents in the construction site that are compatible with the variables required by each rule, and selecting only those configurations of agents that satisfy the rule preconditions. Each configuration of agents that satisfy a rule is called an environment satisfying that rule. Note that the same rule can be satisfied by several environments, meaning that the same rule can generate multiple vocal interactions targeting different agents at the same time (for instance, to raise their attention or to ask for confirmation about the task they are executing on the field).

The latter stage, Vocal Interaction, involves generating an audio file whenever a rule is found enabled during the Construction Site Monitoring stage (Fig. 2). In case the NLP sentence associated with the rule is an open-sentence with parameterized expressions in it, the Vocal Interaction stage receives from the Construction Monitoring Site stage the environments satisfying the rule, and by binding the parameters of each such environment to the open-sentence a closed-sentence is obtained and converted to an audio file using text-to-speech cloud services. Finally, such audio file is routed to the workers associated with the enabled rule. It should be specified that rule activation has no effect on the environment except for voice interaction.

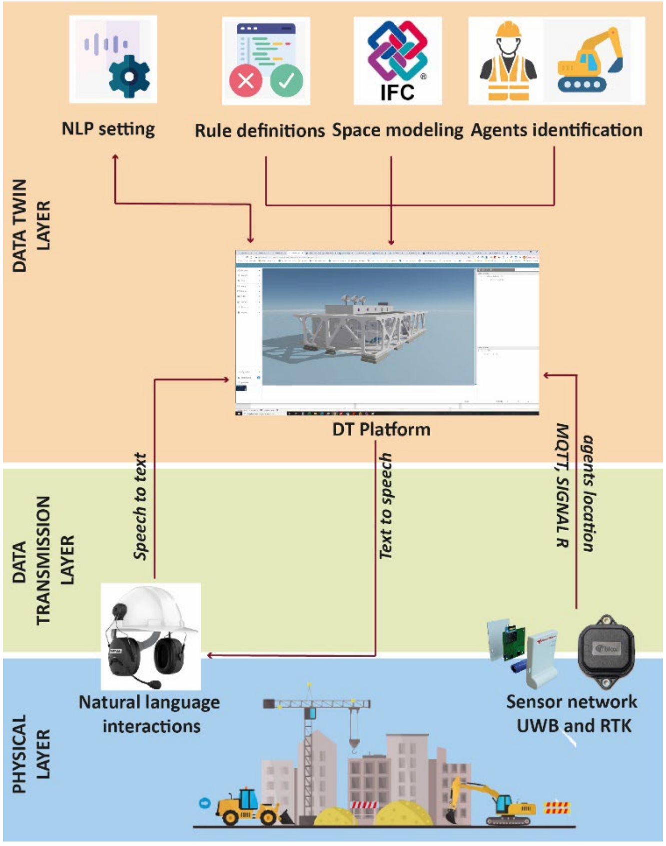

Figure 3 - System Architecture

System architecture

The architecture of the proposed system is shown in Fig. 3. The physical layer, typical of any DT, is represented in our case by the construction site, including resources (workers and machinery), definition of spaces and hazards. The connection between the real world and the digital world is represented by the Data transmission layer. In this DT it is not possible to speak only of Data acquisition layer because the system focuses on communication at the construction site through natural language. Therefore, the data transmission layer has on the one hand the task of acquiring data from the construction site through a sensor network, on the other hand, the information from the reasoning part applied to the data is poured back into the construction site through voice interactions performed by the system.

From data transmission layer we move to what we have called DT layer. In this layer of the system there are several components. Into the DT platform goes all the relevant information for site management and it is the platform that invokes the natural language micro-service. The necessary information also already covered in the methodology concerns the definition of the resources involved (workers and means), the rules to be applied and the spaces. The latter are the spaces of the construction site thus work areas, material storage areas, machinery maneuvering spaces, internal roadway areas, etc.

Application development

A simulated construction site has been recreated in order to test a prototype implementing the proposed methodology. The experiment was conducted within the DC3 laboratory of the Polytechnic University of Marche. The laboratory is equipped with a bridge crane and the agents in the simulated construction site were monitored using an UWB sensor network composed of five UWB anchors mounted along the perimeter of the laboratory and seven UWB tags attached to the agents moving in the simulated construction site. The gateway of the UWB sensor network published the coordinates of every tag once per second on a configured MQTT broker, while the web application subscribed the topics of the same broker in order to receive the most updated position for each tag and store it on the database. To enable audio and vocal interaction with the VVA each worker was equipped with a Bluetooth headset and a battery powered Raspberry PI mini PC connected to a local Wi-Fi internet connection. A web application implemented the aforementioned architecture to drive the Safety Manager along the steps of the proposed methodology. The basic entities at the core of the Digital Twin data-model are Equipment, Protective Equipment, Space, and Human Resource. On a different entity type named Construction Site, the Safety Manager creates instances representing each construction site he/she is managing, specifying for each the relevant attributes such as an identifying label, the location of the construction site itself, the date when the works began and the date when they are supposed to end.

Finally, entity type Item collects instances of each family of equipment, protective equipment, space or human resource, and put it in relation with the specific construction site. For example, two entities named “Jane Doe” and “Tom Cobley” respectively can be linked at a single entity labeled “Scraper operator” of type Human Resource, and at the entity of type Construction Site with label “Gotahm City Central Hospital”. This example clearly identifies two (working) agents in a specific construction stie. They can also be linked to two different entities of type Human Resource, such as “Team A” for “Jane Doe” and “Team B” for “Tom Cobley”. As a different example, the Safety Manager may add an entity of type Item named “Parking Area” that is linked to an entity of type Space labeled “Team A Working Area”, while a second Item may be labeled “Warehouse” and be linked to an entity of type Space named “Team B Working Area”. In the web application, an entity of type Tag is stored on the database for each of the UWB tags, together with their relevant data, viz. the tag identifier, a label for it, the last known position, and the time when the position was detected by the UWB sensor network. Each Tag entity is linked to the entities of type Item mentioned earlier. The next task of the Safety Manager is to model the sentences the VVA should pronounce. Here is the list of template sentences and questions used for our simulated construction site:

S1: {{ A.name }}, the bridge crane requires the following personal protective equipment: {{ PPEs }}. Can you confirm you are wearing all of them?

S2: {{ A.name }}, it appears you are operating on the Bridge Crane {{ B.name }} as though you are not assigned to this task. Are you sure you are allowed to do it?

S3: Watch out {{ A.name }}! You are in danger because the crane is above you

S4: {{ A.name }}, it appears you are working outside the area you are assigned to.

Finally, the Safety Manager can specify the rules that defines the set of events triggering a sentence or a question. Rules are formalized as a logic precondition, associated with a sentence that is to be spoken by the VVA.

Rules are associated with typed variables and the following sentences have been associated to actual implementations:

- distance : it takes two 3-dimension coordinates and computes the linear distance between them
- above : it takes two 3-dimension coordinates and computes the linear distance on the XY plane, thus checking if one of the objects is close or above the other

Below are examples of rules tested in the simulated environment:

- R1: \exists A:Human Resource, \exists B: Equipment. (B.identifier == “BridgeCrane” and distance(A,B) < 0.5 and A.identifier == “BridgeCraneOperator”)
- R2: \exists A:Human Resource, \exists B: Equipment. (B.identifier == “BridgeCrane” and distance(A,B) < 0.5 and A.identifier != “BridgeCraneOperator”)
- R3: \exists A:Human Resource, \exists B: Equipment. (B.identifier == “BridgeCrane” and above(A,B))
- R4: \exists A:Human Resource, \exists B: Space. (B.identifier == “Team A Working Area” and A.identifier == “Team B”)

Rules are associated to sentences as follows: (R1, S1), (R2, S2), (R3, S3), and finally (R4, S4).

The most expensive task of the implemented system, in computational terms, is the construction monitoring phase, re-evaluating rules preconditions in search for environments satisfying the rules themselves and required in order to transform open-sentences onto closed-sentences ready to be reproduced on the workers’ headsets.

Results

In order to carry out an initial verification of the proposed framework, three tests were planned:

- TEST 1: identification of interference risk situation between overhead crane and worker and subsequent voice warning;

Figure 4 - DC3 lab tests, from left to right: test 1, test 2 and test 3.

- TEST 2: verification of possession of the qualifications for handling a construction site machinery (represented by the overhead crane) and vocal communication of any non-possession of the above requirements;
- TEST 3: verification of possession of permits to access areas of the construction site.

Figure 4 and 5 show the setting of the tests performed. In the first scenario, the hook of the overhead crane from which the load was hung was instrumented. The worker, on the other hand, was instrumented with a badge attached to the vest. The minimum distance below which the system sent a warning was set equal to 50 cm, and the warning sent to the worker via Bluetooth earpiece said "Alessandro (worker name) you are about to make contact with the overhead crane (equipment). In the second case, the worker (who always wears the sensor) holds the remote control of the bridge crane, which is also instrumented with a sensor for tracking. In this case, the minimum distance at which the warning starts is 20 cm, and the warning received by the worker is "Alessandro

Figure 5 - Localization tag inside the DC3 lab during tests.

you are/are not in possession of a license to drive the overhead crane." Finally in the last case tested, the cones are instrumented with UWB sensors to detect location and the worker also has the sensor for location. In this case the area identified by the cones is connected with an area defined in BIM for which access rules have been introduced in the system. In the latter test in case the worker sensor overlaps with the identified area, the system reports "Alessandro you do not have permission to access this area."

Conclusions

Safety management at construction sites is a complex problem in which recent technologies still struggle to establish themselves. In addition to reasons such as the economic investment required and the low perception of the usefulness of the proposed innovations, there is also the fact that changing processes or standardizing them in an industry that has never worked on rationalizing procedures is seen as a difficulty in addition to the others already mentioned. For this reason, Safety II proposes an approach to safety that, rather than imposing standard procedures, strives to find ways to make them follow naturally and integrated into operations. With this in mind, this research work aims to integrate natural language within processes through collaborative monitoring techniques. Initial tests have demonstrated the feasibility of the system and the effective development of this initial integration.

The next steps involve studying the best tool for voice communication on the construction site. A helmet with integrated headphones could be a solution whose feasibility should be investigated. Further testing should also be done at construction sites since an important limitation of the proposed approach could be the noise present at the construction site, which could adversely affect message comprehension. Finally, a systematization of knowledge about safety could be implemented for the purpose of testing the scalability of the system to all site operations. Another main limitation of the current research lays in the non-optimized implementation of the rule engine, that at the moment is based on Python and capable of handling only small construction sites. Nevertheless, state-of-the-art and freely available SAT-solvers such as Chaff or Z3 are highly optimized to handle existentially quantified first-order boolean formulas over rational numbers and find environments that satisfy them in systems made of thousands of actors, thus making the methodology feasible even for real-world scenarios.

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