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Development of a Digital Twin Model for Real-Time Assessment of Collision Hazards

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Abstract

The AEC industry is nowadays one of the most hazardous industries in the world. The construction sector employees about 7% of the world's work force but is responsible for 30-40% of fatalities. As statistics demonstrate, interferences between workers-on-foot and moving vehicles have caused several injuries and fatalities over the years. Despite safety organizational measures, passive safety devices imposed by regulations and efforts from training procedures, scarce improvements have been recorded. Recent research studies propose technology driven approaches as the key solutions to integrate standard health and safety management practices. This is motivated by the evidence that the dynamics of complex systems can hardly be predicted; rather a proactive approach to health and safety is more effective. Current technologies installed on construction equipment can usually react according to a strict logic, such as sending proximity alerts when workers and equipment are too close. Nevertheless, these approaches barely do make informed decisions in real-time, e.g. including the level of reactiveness of the endangered worker. In similar circumstances a digital twin of the construction site, updated by real-time data from sensors and enriched by artificial intelligence, can pro-actively support activities, forecasting dangerous scenarios on the base of several factors. In this paper a laboratory mock-up has been assumed as the test case, supported by a game engine, which is able to replicates the job site for the execution of bored piles. In such a scenario populated by an avatar of a sensor-equipped worker and a virtual driller, a Bayesian network, implemented within the game engine and fed in runtime by sensor data, works out collision probability in real-time in order to send warnings and avoid fatal accidents.

Keywords: artificial intelligence, building information modeling, digital twin, real-time system, real-time health and safety management

1. Introduction

The AEC industry represents nowadays one of the most hazardous productive sectors [1]. In fact, it employs only about 7% of the world's work force but is responsible for 30–40% of fatalities. Statistics, referred to different countries, demonstrates that the construction safety is a perennial global problem. In United States the census data from the U.S. Bureau of Labor Statistics (BLS) showed that a total of 774 workers died from injures they suffered on construction sites in 2010, accounting for 16.5% of all industries. The fatality rate (9.8 per 100,000 full-time equivalent workers) ranked the fourth highest among all industries. Within the two decades 1990 and 2000 more than 26,000 U.S. construction workers have died at work. That equates to approximately five construction worker deaths every working day [2]. Over six hundred construction worker deaths, occurred in the United States during the inclusive years of 2004 to 2006, were related to construction equipment and contact collisions [3]. The statistic can be explained by the dynamic work tasks which take place in construction sites and involve multiple resources, such as personnel, equipment and materials. These resources are often in motion and can come in close proximity to each other; because of the unstructured and almost random movement of the manifold of resources involving different trades on job sites, available space can be temporarily limited or constrained. If not coordinated and organized properly through optimized work planning, spatial interference can lead to incidents. One of the main safety problems in construction has been identified as the proximity of workers-on-foot to heavy construction equipment. Lower awareness and loss of focus due to fatigue, task repetition and blind spots affect the totality of construction sites' actors. Current technologies installed on construction equipment can usually react according to a strict logic, such as sending proximity alerts when workers and equipment are too close [3], and provide an estimation of working areas in order to prevent collision accidents [4]. Nevertheless, these approaches barely do make informed decisions in real-time, e.g. including the level of reactiveness of the endangered worker.

The current research develops a twin model of the Digital Construction Capability Centre (DC3), using Unity 3D, to simulate the execution of bored piles. The serious game application implements a Bayesian network which, fed by data from sensors, provides in real-time the linear, rotational and overall collision probability affecting workers-on-foot. This paper is organized as follows. Section 2 provides a description of applied technologies and introduces the developed system architecture. Section 3 reports the experiments and the related results. Section 4 is devoted to conclusion.

2. Materials and methods

2.1 Development of the digital twin in a gaming environment

The digital twin concept, that is the real-time virtual representation of a physical entity across its life-cycle, originates from the manufacturing industry in the early 2000's [5]. In the near future, digital twins will take a center stage in the Architecture, Engineering and Construction (AEC) industry as an instrument to support better informed decisions [6]. Sensors data will be delivered from the real environment, such as a construction jobsite, to its virtual mirror; here, fast forward simulations based on AI technologies can help to predict future scenarios. The development of a building's digital twin requires to model the environment, which includes physical space, sensors and mechanical physics. For the purpose of this paper, a serious gaming platform, namely Unity 3D, has been adopted. The physical space of the digital twin, assumed as case of study, can be directly imported within Unity 3D as an IFC project with its structure. To this end, the IFC Loader, based on the IFC Engine DLL library, has been developed in order to import topological information, materials properties and all semantic information from the digital model. This tool models the environment using one of the most powerful technique in solid modelling: boundary representation (B-REP). B-REP represents a solid as a collection of connected surface elements, that is the boundary between solid and non-solid. The digital twin, in order to mimics reality, requires the implementation of human and artificial sensors, known as agents. The sense of sight, for example, must be implemented in digital twins to give humans' avatars the awareness about what is happening around them. In Unity 3D, this can be done modelling the field of view (FOV) as a collider; a user can see an entity simply if her/his FOV collider intercepts the entity itself. The mechanical physics is a native functionality of game engines; hence, in the game scene every object is affected by gravity just like in reality. To conclude, Unity 3D hosts the digital twin and can work as a hub able to trigger co-simulations related to some specific discipline and receive back results. In this way, multiple simulators (e.g. fire scenario, plants' functioning, etc.) can be coupled, by means of the models exchange standard FMI.

2.2 Bayesian networks

Bayesian networks (BNs) are a computational tool for the development of qualitative probabilistic models. They are oriented graphs whose nodes represent random variables that are linked by arcs which correspond to casual relationships among previous nodes. BNs make use of probability theory and graph theory to make decisions in conditions of uncertainty. The potential of the BN instrument lies in its dual structure. The first one is a set of nodes representing system variables. Each variable may be given two or more possible states which can be of numerical (i.e. discrete), interval (i.e. subdivision into ranges), label or

Boolean type. The second one is a set of links representing the casual relationships between nodes. An arc from any set of *n* variables, called a_i, to another variable *b* denotes that the set a_i causes *b* and a_i are said to be the parents of *b* (*b* is their child). The graphical part illustrates and communicates the interactions among the set of variables through a Directed Acyclic Graph (DAG). Furthermore, Bayesian networks represent the quantitative strength of the connections between variables, allowing probabilistic beliefs to be updated automatically as new information becomes available, by applying the principles of the Bayes' theorem [7]. The strength of these relationships is quantified by conditional probability tables (CPTs), where the probability of observing any state of the child variable is given with respect to all the combinations of its parents' states. These probabilities are usually labelled $P(b|a_1, a_2, \ldots, a_n)$, where any variable a_i is conditionally independent of any variable of the domain that is not its parent. Thus, it is possible to obtain a conditional probability distribution over every domain, where the state of each variable can be determined by the knowledge of the state of its parents only, and the joint probability of a set of variables *E* can be computed by applying the "chain rule" [8]:

$$P(E) = P(E_1, E_2, \ldots, E_n) = P(E_n|parents(E_n))$$

The joint probability of a set E_n of variables is equal to the conditional probability of the variable, given only its parents. Other relevant benefits are: the DAG provides a clear understanding of the qualitative relationships among variables; every node can be conditioned upon the acquisition of new information; belief updating of nodes is supported from consequences to causes, also known as diagnostic reasoning. Finally, CPTs can describe the relationships among variables of different types (e.g., Boolean nodes, interval node, etc.), even within the same network.

In H&S management BNs can be applied to compute the probability of a hazardous scenario to occur, on the base of real-time sensors data. For the purpose of this paper, a Unity 3D tool, namely Discrete Bayesian Network, has been applied for the implementation of BNs inside the serious gaming platform. This tool provides a C# library that facilitates the definition of BNs' structure and parameters regulating Bayesian inference.

2.3 Digital Construction Capability Centre

The Digital Construction Capability Centre (DC3) is a hologram room of about 240 m^2 situated at the Polytechnic University of Marche in Ancona, Italy; the facility is dedicated to digital twin applications such as construction scenario simulation, innovative teaching approaches and operations scenario simulation. To make it possible, a twin model of the DC3 has been developed as a mock-up which, continuously updated by real-time data from sensors, constitutes a virtual replica of reality.

The DC3 mock-up is based on the system architecture shown in Fig. 1 and composed by the following technologies: a set of UWB position sensors, Node-RED programming tool, Arango DB database and Unity 3D game engine. In the DC3 environment, workers simulating field activity can be located by means of an UWB localization system. This technology leverages Time of Flight (ToF), which is a method for measuring the distance between two radio transceivers by multiplying the Time of Flight of the signal by the speed of light; thus, knowing the position of fixed UWB anchors and operating a trilateration, the position of moving UWB transceivers (tags) can be determined. For the purpose of this paper, five anchors have been installed in known positions, whereas two UWB tags have been applied to the safety jacket in order to track position and heading of the worker-on-foot who wears it. In order to wire together hardware devices (IoT) with the database and then with the Unity 3D game engine, the flow-based graphical programming tool Node-RED has been adopted. It provides an open-source browser-based graphical editor that allows to build complex flows using a wide range of nodes provided in the palette and by the community. In this research, a dedicated Node-RED flow wires together the position data coming from the UWB localization system with a database for their storage. This flow interfaces with the UWB localisation system (MDEK1000 by DecaWave) by using the MQTT protocol. When building a digital twin, different types of data have to be stored and linked together in an emerging way. Therefore, ArangoDB has been selected here as native multi-model NoSQL open-source database also for storing the complete data history from sensors. In order to allow Node-RED to access ArangoDB, a specific Node-RED node has been developed for writing JSON documents into a collection of an ArangoDB database by using the ArangoJS language. The hearth of the developed architecture is the serious game engine Unity3D, which hosts the digital twin and enables AI-based simulation to predict dangerous scenarios. On the base of sensors data stored in ArangoDB, the continuous update of the Unity3D scene has been made possible by SignalR software library, which sends asynchronous notifications to client-side web applications. As a consequence, position and rotation coordinates of the monitored worker-on-foot are delivered to a virtual avatar in order to mimic her/his behavior. In this research study, the AI component, implemented inside the serious gaming platform, is represented by a Bayesian network designed to predict collision hazards between workers-on-foot and moving equipment, such as a drilling machine. Finally, a dedicated web application, installed on the equipment's on-board computer, can make results from AI-based assessment available to the driver. The aim of this field application is to make the driver aware about oncoming risks, affecting vulnerable users in the job site, in order to prevent fatal events.

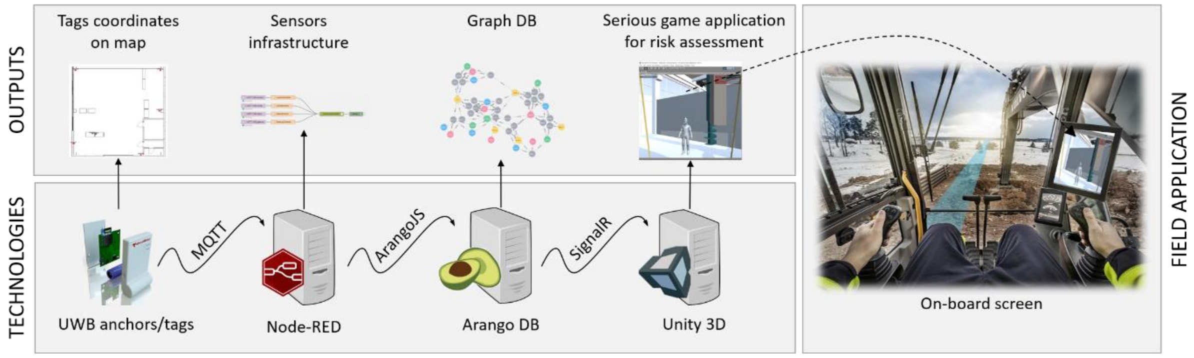

Fig. 1. System architecture

3. Experiments

3.1 Development of the mock-up and design of the experiment

For the purpose of this research study, the execution of bored piles has been assumed as test case scenario, since it represents one of the most hazardous construction procedures. In fact, a worker-on-foot is called to work close to heavy components, such as the drilling machine, during each phase. To make a few examples, the workers-on-foot leads the positioning of the bucket at the exact drilling point, assists the insertion of the reinforcement cage, opens the bucket to unload the extracted soil and supervise the concrete filling. During the described operations, a momentary lapse could lead to injuries and fatal events. For this reason, AI applications could greatly benefit real-time H&S management.

In this paper, the digital twin of the DC3 has been applied to develop a serious game application which support real-time H&S management. To this aim, a DC3 mock-up which replicates drilling operations has been implemented using Unity 3D. As introduced in section 2.1, the real environment has been recreated loading the IFC model of the DC3. The implementation of the UWB localization system, described in section 2.3, makes it possible to track the position of the workers and equipment. A worker-on-foot, wearing a sensorized jacket, can be monitored and replicated by an avatar who lives the virtual scene. The mock-up is completed by the virtual model of a drilling machine, which is controlled by a joystick in order to simulate a real working scenario. The BN shown in Fig. 2 assesses the probability that the drilling machine runs over the worker-on-foot given, as evidences, the linear distance driller-worker, the angle between the driller's forward direction and the line driller-worker, the driller's linear and angular speed and, finally, the mutual visibility. Being the BN implemented in Unity 3D by means of the Discrete Bayesian Network tool, as mentioned in section 2.2, the twin model receives real-time data from sensors and feeds BN's variables. The pseudocode shown in Fig. 3 describes the implementation of a portion (see the red dashed line in Fig. 2) of the Bayesian network, developed for collision risk assessment, inside the serious gaming platform; the resulting linear collision probability is the probability that the drilling machine runs out the worker-on-foot. The rotational collision probability is instead the probability that the rotating body of drilling machine hits the worker-on-foot. Finally, the overall collision probability summarizes the two previous variables providing an overview of the hazards affecting the worker-on-foot.

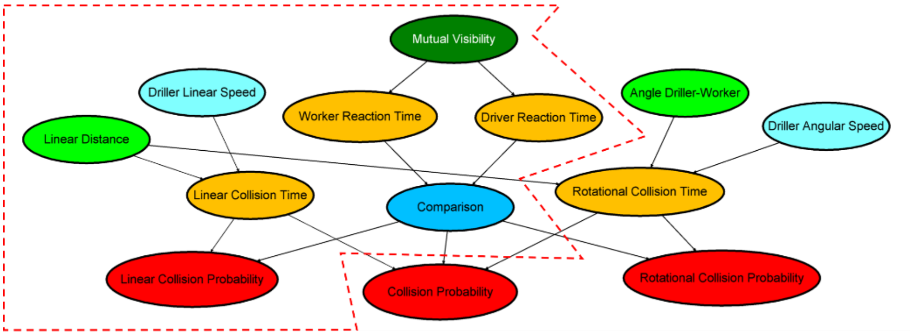

Fig. 2. The Bayesian network developed for the collision risk assessment

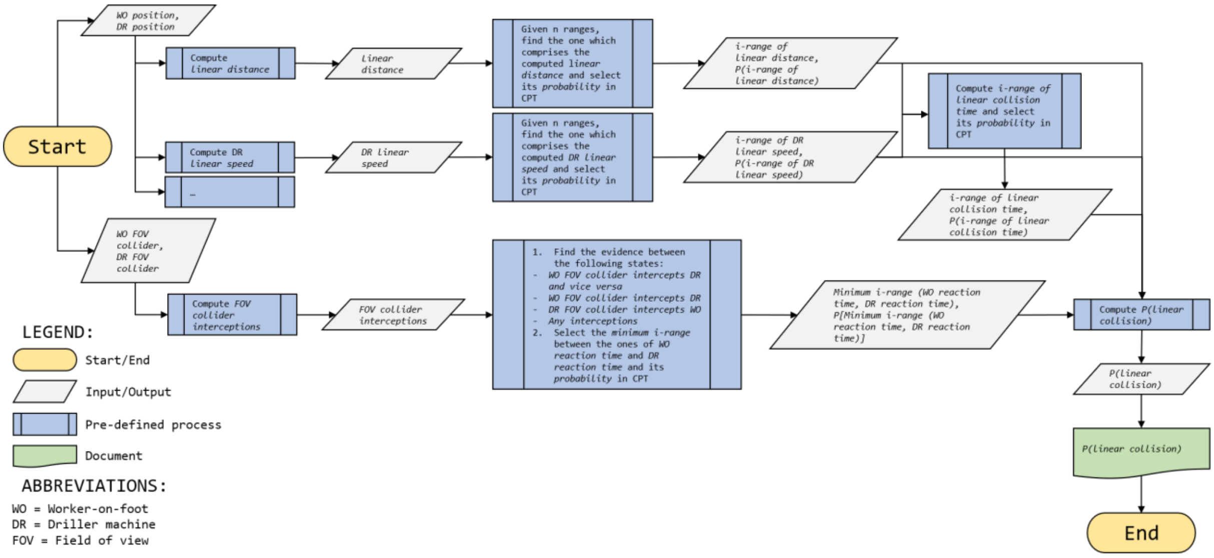

Fig. 3. Pseudocode describing the implementation of a portion (see the red dashed line in Fig. 2) of Bayesian network in Unity3D game engine

3.2 Experiments and results discussion

In this paper, drilling operations for the execution of bored piles have been simulated by two researchers. The first one wears the sensorized safety jacket and moves around the construction site in order to mimic the support activities accomplished by a worker-on-foot during drilling operations. The other researcher controls the virtual drilling machine by the joystick. This scenario is mirrored by the DC3 mock-up in Unity 3D on the base of real-time data provided by sensors. According to this data, the BN implemented in the serious game engine computes and updates linear, rotational and overall collision probabilities in real-time. In Fig. 4.a, the ground worker can see the drilling machine (see FOV colliders represented by green lines in Fig. 4.a), while the driver has a reduced visibility; nevertheless, the BN does not point out risks due to the distance between the worker-on-foot and the drilling machine. In Fig. 4.b, the visibility conditions keep unvaried whereas the linear collision probability rises from 0% to 24.51%, since the linear distance has decreased. In Fig. 4.c the worker-on-foot turns her/his back to the drilling machine; since the worker and the driver cannot see each other (see FOV colliders represented by green lines in Fig. 4.c), the linear collision probability increases up to 51.09%.

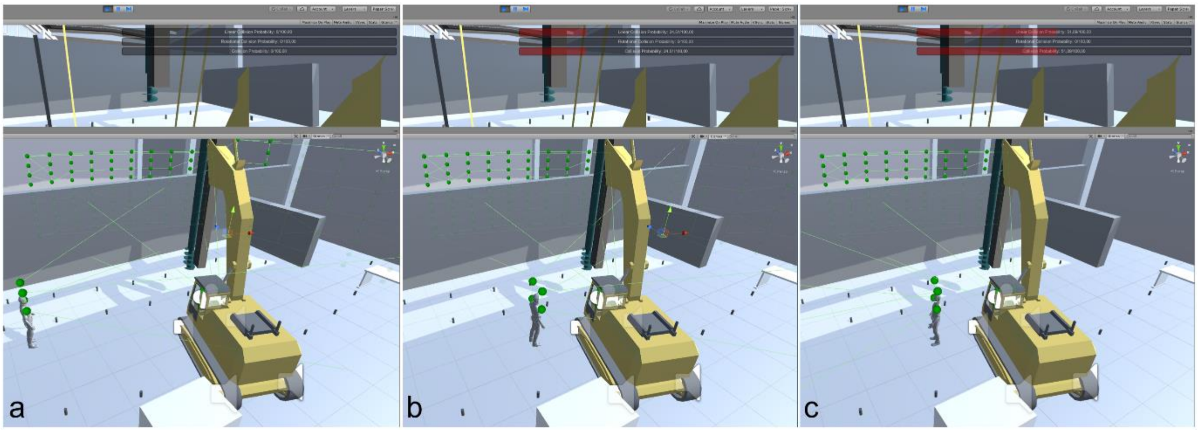

Fig. 4. The BN updates of the linear collision probability according to the changing environment conditions

4. Conclusions

The complex nature of construction sites makes it difficult to predict hazardous scenarios affecting workers. In similar circumstances, a digital twin of the job site, automatically updated by real-time data from sensors, can pro-actively support activities and forecast dangerous scenarios by means of AI technologies.

In this paper, the twin model of the Digital Construction Capability Centre (DC3) at the Polytechnic University of Marche (UNIVPM) has been developed as a mock-up using a gaming engine. The result is a serious game application which implements a Bayesian network to compute collision probability during drilling operations, based on several relevant variables. This technology can be applied to inform the equipment's driver about oncoming risks in real-time; hence, it aims to improve her/his awareness in order to avoid injuries and fatal events.

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6. References

[1] Zhou, Z., Goh, Y.M., Li, Q., 2015. Overview and analysis of safety management studies in the construction industry. Safety Science 72, 337–350. http://doi.org/10.1016/j.ssci.2014.10.006.

[2] Zhang, S., Teizer, J., Lee, J.K., Eastman, C.M., Venugopal, M., 2013.Building Information Modeling (BIM) and Safety: Automatic Safety Checking of Construction Models and Schedules. Automation in Construction 29, 183–195. http://doi.org/10.1016/j.autcon.2012.05.006.

[3] Teizer, Jochen & Allread, Ben & Fullerton, Clare & Hinze, Jimmie. (2010). Autonomous Pro-Active Real-time Construction Worker and Equipment Operator Proximity Safety Alert System. Automation in Construction. 19. 630-640. https://doi.org/10.1016/j.autcon.2010.02.009.

[4] Chae, Soungho & Yoshida, Tomohiro. (2010). Application of RFID technology to prevention of collision accident with heavy equipment. Automation in Construction. 19. 368-374. https://doi.org/10.1016/j.autcon.2009.12.008.

[5] Kritzinger, W., Karner, M., Traar, G., Henjes, J., Sihn, W., 2018. Digital Twin in manufacturing: A categorical literature review and classification. IFAC-PapersOnLine 51, 1016–1022. http://doi.org/10.1016/j.ifacol.2018.08.474.

[6] Bentley System Inc., 2019. Advancing BIM: Digital Twins. Technical Report. Bentley.

[7] Catenacci, M., & Giupponi, C. (2009). Potential of Bayesian Networks to deal with uncertainty in climate change adaptation policies. CMCC Research. https://doi.org/10.2139/ssrn.1526605.

[8] Pearl, J. (1988). Probabilistic reasoning in intelligent systems: Networks of Plausible Inference (2nd ed.). California: Morgan Kaufmann Publishers. ISBN:978-1-55860-479-7.