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A Digital Twin for Safety and Risk Management: a Prototype for a Hydrogen High-Pressure Vessel*

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Abstract. The term "digital twin" refers to an emerging technology that utilizes the internet of things, software simulation, and data analytics to create a digital replica of a physical object or system. Digital twins have the potential to significantly transform condition monitoring and maintenance operations. In this research, a prototype is developed consisting of hardware and software components to enable the creation of a digital twin for an industrial application. High-pressure hydrogen vessels are industrial equipment with a high safety requirement for the storage and transfer of highly flammable hydrogen. Our prototype illustrates the effectiveness of utilizing a real-time digital twin of the hydrogen high-pressure vessel for failure risk management. The Action Design Research (ADR) is used to describe the process that led to the development of the prototype.

Keywords: Digital twin · Action Design Research · Risk management.

1 Design of the Artifact

The prototype we present in this paper is the result of a rapid design and development effort, taking place within the context of a hackathon. Although not yet implemented, our prototype and the design process leading to it offer both practical and theoretical insights from the perspective of design science [1, 2]. The practical relevance of our prototype is that it has the potential to improve the safety of an environmentally friendly energy source—saving lives in both the short and long term. By searching for a solution to our practical design problem [1]—how to improve the safety of hydrogen high-pressure vessels—we also probe the theoretically interesting problem of how to close the feedback loop between the real and the digital world. Our prototype can be described as an ensemble artifact [2], and in this paper we elaborate upon its emergence and its significance. As the prototype was developed over the course of a hackathon, the

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design process represents a high-paced pragmatic balancing act between technical rigor and relevance for the industry problem. In terms of Design Science methodology, we argue that the hackathon encompassed much of what can be expected from an ADR project [2]. What follows is a description of our prototype, combined with a retrospective account of the key considerations emerging throughout the design process, mapped against the ADR method stages [2].

1.1 Problem Formulation

In terms of problem formulation, industry hackathons encompass the principles of ADR. The event is initiated different companies presenting problems for which they would like to explore solutions, representing an opportunity for practice-inspired research [2]. The hackathon participants then form teams around one of the presented problems, depending on personal preferences and interests. When researchers participate in hackathons, they are bound to choose problems, which resonate with their theoretical understanding and background, ultimately resulting in a theory-ingrained artifact [2]. In our case, the interesting problem was how to improve the safety of hydrogen storage, distribution, and transportation (in accordance with applicable codes and standards (AIAA G-095-2004)):

Hydrogen is a potential energy carrier for the future [3]. After its production in plants, hydrogen is stored and then transported to the demand points. The use of high-pressure vessels is generally prevalent for the storage and transportation of hydrogen (liquid and gas); therefore, there is always a risk of explosion along its supply chain. In recent years, several incidents related to hydrogen explosions have occurred. In particular, the hydrogen explosion at the Fukushima nuclear power plant [4] caused the most severe nuclear accident since the Chernobyl disaster. Considering the financial and life losses resulting from a hydrogen explosion, it is imperative to fully understand and investigate the safety issues related to this chemical element.

1.2 Building, Intervention and Evaluation

Throughout the hackathon, the company representatives (problem owners), actively spar with the participating teams, providing instant reflection and feedback on the emerging ideas. Here the problem owner represents the organizational context, and the sparring leads to reciprocal shaping of the artifact with built-in authentic and concurrent evaluation [2]. Further, companies participate in industry hackathons to get insight in novel (often technological) solutions approaches, whereas participating teams get insight into the industry and its inherent challenges, leading to mutual learning between solution owners and participating teams [2]. In our case, throughout the hackathon, there was several such in-depth exchanges, resulting in several cycles of iterative artifact development. We set out to build a solution based on the concept of a digital twin:

Digital twins will "facilitate the means to monitor, understand, and optimize the functions of all physical assets by enabling the seamless transmission of data between the physical and virtual world [5]." In the case of hydrogen storage, distribution, and transportation, our proposed design involves applying a digital twin, whose process is illustrated in Fig. 1. The digital twin's real-time connection to hydrogen vessels provides condition monitoring. Therefore, the operator (in the control center and tanker truck) can receive more intelligent and actionable messages in the appropriate time to reduce the risk and prevent an explosion.

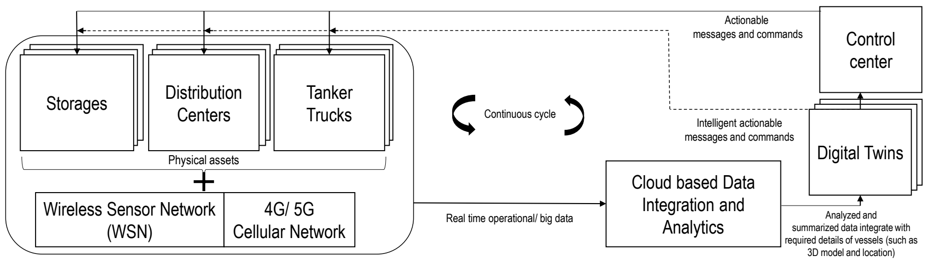

Fig. 1. Deployment of digital twin in hydrogen storage and transportation.

To monitor the status of hydrogen and to create a digital twin of a hydrogen vessel, a number of measurements are required, such as hydrogen concentration, pressure, and temperature. Moreover, the operator must track all hydrogen vessels during transportation for better decision-making. Remote systems based on sensors need to transform data to cloud by using networks; in this regard, 5G will transfer a substantial amount of data 10 times faster than 4G networks. To create the WSN considering the required measurements and 5G deployment, the proposed prototype utilizes a number of sensors and micro controllers as follows: BME680, MQ-8, Arduino MKR NB 1500, ESP8266.

The various sensors present in the hydrogen vessel send real-time measurements to an online database, which enables other devices to retrieve both the most recent measurements and historical data. A program written in Python is responsible for retrieving the latest data from the REST API, processing it using the data analytics algorithm, and making the results accessible to the operator by pushing it to the MindSphere platform. Moreover, for the data analytics, the Jaribion et al. method [6] is used to simplify the big data for the operator. By utilizing this method, the system is constantly calculating the similarity of the data collected from sensors (hydrogen concentration, pressure, and temperature) to the ideal reference point, which is set in accordance with applicable codes and standards for hydrogen maintenance. According to [6], the sensor measurements are represented by $\tilde{A}$, while the ideal reference point is represented by $\tilde{B}$, and the similarity to ideal reference point is calculated by $S(\tilde{A},\tilde{B})$ in (1).

$$S(\tilde{A},\tilde{B}) = \left(1 - \frac{\sum_{i=1}^{4} |a_i - b_i|}{4}\right)^{\left(1-|x^*_{\tilde{A}} - x^*_{\tilde{B}}|\right)} \times \frac{min\left(P(\tilde{A}),P(\tilde{B})\right)+min\left(a(\tilde{A}),a(\tilde{B})\right)}{max\left(P(\tilde{A}),P(\tilde{B})\right)+max\left(a(\tilde{A}),a(\tilde{B})\right)} \quad (1)$$

The analyzed data is integrated with the required details of the vessels, such as the 3D model and location, in order to create the digital twin of the hydrogen vessel. Although we used the Unity engine for this integration in the proposed prototype, the use of specialized digital twin software is recommended. By visualizing the digital twin at the control center, through an easy-to-use responsive front-end interface, the operator can monitor the hydrogen status, diagnose the fault, identify the fault location, and send actionable messages and commands to the storage unit or tanker trucks. Furthermore, the digital twin can directly and intelligently send actionable messages and commands to the storage unit, or tanker trucks without interference from the control center.

1.3 Reflection and Learning

As elaborated above, the hackathon creates an environment for mutual learning. On one hand, during the hackathon, the problem owner learns of several approaches to tackling the problem at hand. During the hackathon the different emerging artifacts are subtly shaped by the solution owner through the advice and opinions he presents to the participating teams, while the solution owner's insight into the potential of the technological or theory-ingrained approach evolves. Conversely, researchers participating in the hackathon expose themselves to a new context, which widens their perspective of the potential of their underlying theoretical and technological understanding to solve problems.

1.4 Formalization of Learning

In the fourth stage of ADR, we reflect upon the hackathon, and ask what we as researchers learned from it. Considering our solution, we note that the implementation of a WSN does not require or highly rely on existing asset instrumentation, thus allowing for fast rollout, through retrofitting with hardware and software improvements, and adjustments in currently in-use vessels. Moreover, using 4G/5G cellular networks, which leverage existing wireless communications infrastructure, allows for usage on stationary and mobile assets. In addition, cloud-based data integration and analytics bring scalability and flexibility without the need for a significant initial investment in data storage and processing. When the digital twin is created, this real-time intuitive digital representation of the asset will create situational awareness and produce actionable insight for dependent users, and the operator can then act accordingly. Overall, having a digital twin monitoring the location and status of all the vessels will provide real-time information regarding impending problems; enhance control and safety from the level of no automation to full automation; and mature digital transformation from simple control toward analytics supporting decision-making, deep learning, and predictive analytics (see Fig. 2).

In terms of the three levels for generalizing learnings from ADR-projects [2], we formalize as follows: (a) The problem instance can be generalized to creating real-time situational awareness of a heterogeneous (both in terms of type and age of assets), dispersed and potentially mobile asset base. (b) The solution instance can be generalized as a digital twin of an engineering asset. Finally, we can, based on our hackathon experience—where a working prototype of the solution was produced in 48 hours—state the following (c) design principles (DP):

DP1: A digital twin enables a scalability in creating situational awareness of an engineering asset base, as it accommodates asset base heterogeneity.

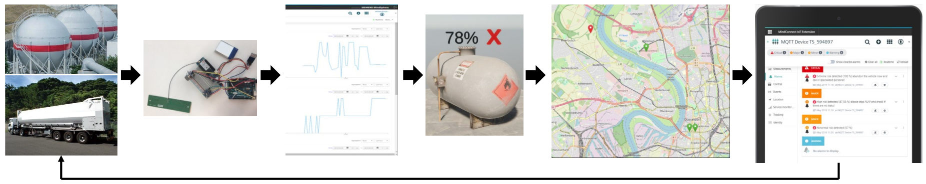

Fig. 2. The digital twin of the hydrogen vessel in action.

DP2: A digital twin enables a quick development of situational awareness of an engineering asset base, through enabling the use of existing infrastructure for data acquisition, communication, data processing and data visualization.

2 Significance to Research

The manifestation of renewable energy, such as hydrogen, requires safe storage and transportation from the production site to users. Conducting research and harnessing new technologies in this field are hence necessary [7]. Digital twin technology is among the top strategic technologies in recent years, and according to research's future predictions, "the digital twin market will reach 15 billion dollars by 2023" [5]. In the context of hydrogen storage, some articles present new mathematical methods to improve and optimize the design of high-pressure vessels [8]. However, they do not describe any procedure regarding the later use of these sensors for monitoring and fault diagnosis. Abdalla et al. [7] review and point out the safety, reliability, and cost-efficiency of materials for hydrogen storage. On the other hand, although [8] introduces the implementation of sensors during the production of vessels, and [9] discusses primary explosion protection by detecting the unintentional escape of gas in due time, neither presents any solution for improving the safety of existing vessels. Furthermore, while [10] explores the current state of the art in safety and reliability analysis for hydrogen storage and delivery technologies, the mentioned recommendations focus on encouraging companies to reduce future risks and support safe operation.

3 Significance to Practice

Hydrogen gas is highly flammable and has the highest rating of 4 on the NFPA 704, which is a standard system for the identification of the hazards of materials for emergency response [11]. Therefore, hydrogen safety, which covers the production, storage, transportation, and utilization of this element, is of great importance. Moreover, the emergence of fuel cell technology as a green alternative to internal combustion engines powered by fossil fuels signifies the timing of this research. "It is estimated that about 15–20% of all European refueling stations need to be equipped with hydrogen supply" [12]. As the global production volume of hydrogen is projected to increase over the next five years [12], the risks related to its production and handling may grow if new solutions are not adopted. Since the occurrence of large incidents creates a negative public view towards the safety and practicality of fuel cell technology, risk management of hydrogen high-pressure vessels using a digital twin can reduce the adaptation vulnerability of this fragile green technology in today's competitive market.

4 Evaluation of the Artifact

While the prototype has not been tested in the field and thus requires further development, the equipment and software successfully passed initial lab testing and functioned according to the design specification. The presented prototype was developed for a European conglomerate company during a hackathon and one of the company's managers commented on the proposed prototype as follows:

"The presented design points out to an actual topic, since our company is currently working on assuring the safety of hydrogen vessels. A group of our company experts evaluated the presented prototype as an innovative design for utilizing 5G in creation of digital twins and improving its performance. Moreover, the presented design is adoptable and scalable within the market."

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