Development of a digital twin for collaborative decision-making, based on a multi-agent system: application to prescriptive maintenance

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Abstract. The fourth industrial revolution involves more complexity. This research effort focuses on decision-making in helicopter engine maintenance activities. Such a decision-making task is difficult and relies on a variety of experts who only have partial knowledge and incomplete situation awareness, due to the great diversity of everyday operational practices. In this paper, we propose a digital twin multi-agent approach to collaborative decision-making in prescriptive maintenance.

Keywords. Digital twin, decision-support system, maintenance, multi-agent system.

Introduction

The current context of the fourth industrial revolution (Maynard et al., 2015) is as promising as it is a source of complexity. In complex industrial processes, such as maintenance of helicopter engines, our field of study, each stakeholder owns only a part of necessary information, knowledge, skills and knowhow, which induces only a set of partial views for handling current situations. Consequently, decision-making quality and effectiveness are impacted.

The decision-making process is based on personal expertise, techniques and tools that are easily understood in their immediate environment (i.e., entities such as department or team). Unfortunately, sometimes goals and benchmarks are different within teams and/or departments; therefore, mutual understanding and collaboration can be difficult.

Endsley defines situational awareness (SA) as perception of the elements of an environment in a volume of time and space, understanding of their meaning and projection of their state into the near future (Endsley, 1995). SA is recognized as a major issue in such a context.

Many techniques are used to support cognitive tasks in companies like knowledge management (KM) (Aries et al., 2008) or machine learning (ML).

Even if techniques currently used locally look satisfactory, their expansion at the level of the entire company requires more systemic socio-cognitive task analyses toward improving collective performance.

This is the reason why this study is based on a state of the art and a field study leading to a first proposal for a digital twin model to support decisions by integrating companywide knowledge.

State of the art

Cognitive science

Cognitive science and cognition refer to high-level brain activities such as perception, memory, or abstract reasoning (Vignaux, 1991). Understanding cognitive issues is crucial in an industrial environment. Transdisciplinary research for cognitive engineering (Boy, 2003), or "cognitique" in France (Lespinet-Najib, 2013) intents to adapt technology to the human rather than the opposite, to better assist people, by combining knowledge about humans, technology and the relationships between them.

Three main intellectual fields of cognitive science are currently studied:

- Cognitivism which is based on the hypothesis that cognition is a manipulation of symbols enabling the adaptation of solutions to current situations (Pylyshyn, 1986). KM is an example of industrial application of this field.
- Connectionism which is based on the assumption that cognition is the emergence of global states (expected responses) of networks of single elements (such as neurons) (Hebb, 2005). ML is a successful example of connectionism field for tasks such as image or natural language recognition.

The "society of mind" (Minsky, 1986) which corresponds to a hybridization of cognitivism and connectionism. Different cognitive functions are performed by various agents (an agent has a function) which know how to solve a type of small-scale problem. For a larger scale problem, several agents linked together will be needed, this group of agents forms an agency. If we look at different levels, each internal agent organization can be seen as an agency itself. Consequently, cognition can be seen as a working society. This type of operation enables to solve more complex and unforeseen problems.

Decision-support and multi-agent system

Minsky's theory of human cognition implementation led to multi-agent systems (MAS) that enable us to model and simulate collective intelligence. Like a colony of ants, a school of fish or a flock of birds, individuals interacting in their environment are autonomous, at least partially. But relatively simple rules these agents individually follow lead to very sophisticated organizations at the collective level.

The efficiency of cognitive tasks, and more precisely decision is of strategic importance in industry (Villeneuve et al., 2016). As the company can be seen as a system of systems (Popper et al., 2016), a MAS representation can allow the integration of the company's knowledge (Merlo, 2003).

Maintenance

The above notions of cognitive science enable us to tend towards a flexible approach necessary in complex contexts (Boy, 2021). This is intended for application to maintenance of a fleet of helicopter engines, that is to say aimed at maintaining them in operational condition and/or at repairing them. Our work in progress focuses on the identification of the right levels of maintenance maturity.

Different stages have been identified (Nikolaev et al., 2019). We find in ascending order of maturity:

- Descriptive analysis to understand and describe an event that occurred;
- Diagnostic analysis to identify the cause of the event;
- Predictive analytics to predict future events;
- Prescriptive analysis to obtain recommendations on the best possible choices.

The development of the prescriptive level seems to be the best to improve maintenance efficiency.

The digital twin

We have seen previously that in industry, many cognitive tasks can be supported by different techniques and approaches. Their wide diversity can make difficult gaining an exhaustive view of the actual industrial activity and parameters to be considered in decision-making leading to maximize overall efficiency.

Digital twin (DT) technology is recognized as a tool to manage such a complex system (Grieves et al., 2017). Defined by NASA as "an integrated multi-physics, multi-scale, probabilistic simulation of an as-built vehicle or system that uses the best available structural models, sensors update to mirror the life of its corresponding flying twin" (Glaessgen et al., 2012), its definitions evolved in a more generalist way to "a dynamic representation of a physical system using data, models and interconnected processes to enable access to knowledge of past states, present and future to manage action on this system" (Camara Dit Pinto et al., 2021).

Moreover, different levels of data integration have been identified by Kritzinger (Krintzinger et al., 2018). To achieve a dynamic and real-time DT, data flows should be automatic.

State of the art conclusion

It emerged that DT enables bringing collective intelligence to the maintenance activity at the organizational level.

The cognitivist approach enables us to manage high-level problems but lacks flexibility. Unexpected data or a missing rule lead implementations to fail.

The connectionist approach enables performing a large number of cognitive tasks such as recognizing images, texts or statistical trends but is very specialized. A task that deviates a little from what the program was designed and sized for will defeat it.

These two approaches are effective, each in the specific frameworks for which they have been implemented. It appears that a matrix articulating them would be beneficial. Matrix in the biological sense of the term, that is, the tissue in which more specialized structures are incorporated.

To this end, as already cited, Minsky developed an approach around his "Society of Mind" (Minsky, 1986).

More flexible, this approach enables us to understand a complex industry context involving the activity of many actors, humans or machines as an SMA. This is a basis for the design of a DT that reflects them. By modeling them despite their diversity and complexity, we can access predictions according to the known situation and the decisions made, and thus prescribe recommendations. These recommendations would be based on a situational awareness inaccessible to hitherto isolated parties, that is, without the help of a DT that aims to expand into omniscience.

FIELD STUDY

Observations and 21 semi-structured interviews with 15 partners spread over 9 departments were conducted in a helicopter engine maintenance company to see how what has been mentioned in the state of the art applies. A team of engineers in charge of fault diagnostics will look for the origin of a fault reported by a customer and the fastest and least expensive solution for solving the current case. However, the department responsible for fleet and resource management may have relevant information about the consequences of the chosen solution. For example, the longer-term economic cost or the impact on service to a related customer. This is a typical case. Currently, when a department feeds on information from another department, it is made manually or through meetings.

The studied industrial case already deployed several solutions with respect to the following maintenance methods:

- For descriptive maintenance: the collection of flight data in semi-real time following each helicopter flight. This data is collected by on-board sensors and the transfer takes place manually or automatically when the device returns to its base.
- For diagnostic maintenance: experts identify the root cause of failures using software based on a Bayesian network. The probability variables are based mainly on past experience.
- For predictive maintenance: engine health is monitored, and indicators or alerts based on thresholds are developed through statistical analysis of trends (temperatures, rotation speeds, vibration frequencies…) and artificial intelligence.

Cognitive science applied

Cognitivism: knowledge bases have been identified. Experts are invited to capitalize their knowledge in these bases but they are not integrated directly into the activity and thus their updating is not optimal. However, a Bayesian network (used by diagnostic team) is fed by probabilistic expert estimates of the links between symptoms and causes of engine failures. In this case, it is up-to-date as this system is used on a regular basis.

Connectionism: recent successful applications of deep learning have been observed to sort out large amounts of feedback documents written by customers in natural language to help diagnostics and for the detection of significant statistical trends in flight data in the engine health monitoring team.

Data flows

Some data or information flows tend to be as automated as possible, such as the collection of flight data via on-board sensors. However, some remain entirely manual, such as the transmission of information from the support service, comprising an engine health monitoring team and a diagnostic team, to the management of fleets and stocks of resources through regular meetings. This last flow represents a case of horizontal integration where a DT could help.

PROPOSAL: THE MULTI-AGENT SYSTEM AS A MEANS OF DIGITAL TWIN MODELING AND IMPLEMENTATION

It emerged from the state of the art, reaffirmed by the field study thereafter, that in cognitive science, cognitivism and connectionism have led to efficient industrial solutions such as knowledge management or deep learning respectively. But these solutions correspond to very specialized tasks. The concept of the society of mind, leading to solutions such as MAS, opens up the possibility of modeling systems of significant complexity. In helicopter engine maintenance, operators involved, human or machine, and expertise are very diverse. Each operator can be considered as an agent, and therefore the company as a MAS. Since each agent is itself a system, the helicopter engine maintenance activity can also be seen in other words as a system of systems (Boy, 2013) (Boy, 2019).

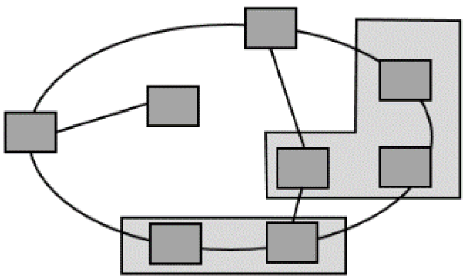

Figure 1. System of systems (Boy, 2019).

The maintenance activity can be represented by a system of systems (Fig 1), corresponding to the physical part of the paired system, whatever the granularity level (part-engine-fleet, individual-team-service etc.). If the physical twin is a system of systems, so should its digital counterpart. Systems that constitute the human parts of this system of systems have of course cognitive capacities which enable them to carry out their activity, but we can also find non-human cognitive systems like AI.

The DT should generate multi-agent cognition, that involves holistic or holonic decision-making processes (i.e., considering all available system states and information). All agents have a common goal. It is currently impossible for each agent to be aware of what other agents are doing in real time. A MAS structure is proposed here to represent this multi-agent cognition.

If we combine the system of systems model with the concept of data integration levels previously seen, it gives a digital system of systems representing the physical system of systems. It is like a digital MAS, and its data flows connecting digital agents to physical agents depend on the level of maturity and/or locally-acceptable level of automation. Non-existent or invisible links within the physical twin can be established or highlighted within the DT for exploitation (Fig. 2).

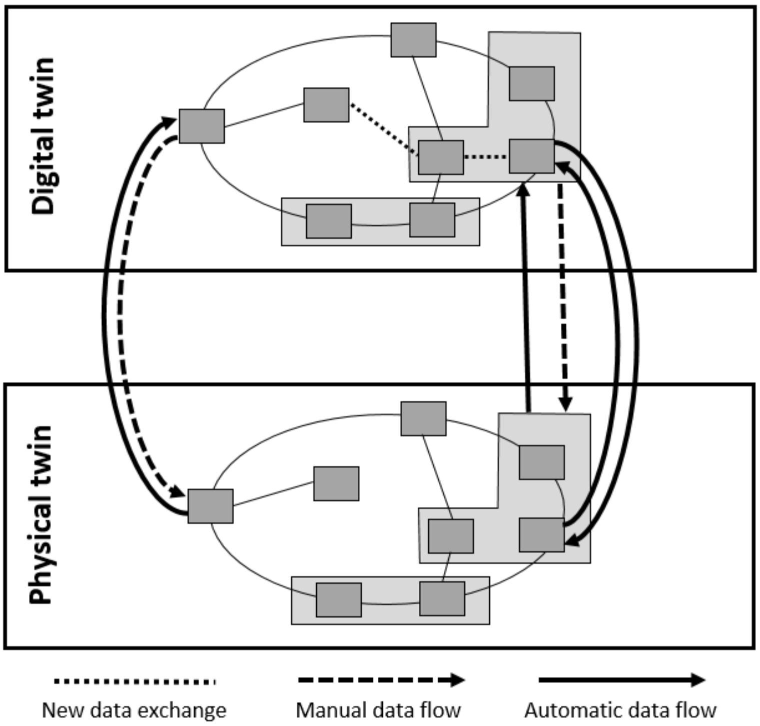

Figure 2: Twin system of systems and data streams inspired by Boy and Krintzinger (Boy, 2019) (Krintzinger et al., 2018).

Given that:

- The MAS seems to provide flexible solutions adapted to a context which includes many individuals and evolving practices;
- The most accomplished form of maintenance seems to be prescriptive maintenance;
- The DT aims to model a physical system and its environment to provide situational awareness;

It appears important to establish as a research objective a digital twin of the helicopter engines and a MAS of the company for prescriptive maintenance and collaborative decision-making at the organizational level.

CONCLUSION AND FUTURE WORK

This work is focused on a MAS as a means of digital twin modeling and implementation for supporting the coordination of maintenance activities and provide better situational awareness. This should lead to better decisions (Endsley, 2000) by improving SA and adding flexibility. It is necessary to create a company-wide DT representing involved and effective actors or agents. DT is intended to prescribe recommendations for each industrial agent or player by specifying possible actions consequences and taking into account collective knowledge and preferences dynamically.

Interfaces that enable each agent to become part of the system will be explored. Finally, we will continue to involve company's stakeholders in the design, in an iterative user-centered design approach.

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Biography

Quentin Lorente obtained a 2-years technological university degree in statistics and business intelligence from the University Institute of Technology in Pau, France, in 2016. Then he graduated from the National Graduate School of Cognitics (ENSC) in Talence, France, in 2019, a multidisciplinary engineering school specializing in Human Centered Design. He is now a Ph.D. student for applied research in the industrial field of collaborative helicopter engines maintenance with Safran Helicopter Engines and ESTIA Institute of Technology, and fellow of FlexTech scientific chair (CentraleSupélec and ESTIA).

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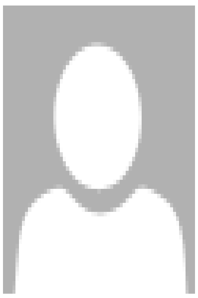

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