Cognitive Mimetics for Designing Intelligent Industrial Systems: Case Next-Generation Diary

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ABSTRACT

A key problem with intelligent industrial processes is that the relevant systems, such as digital twins or cyber–physical systems, require knowledge to perform their operations. Currently, much of that knowledge is in the human domain; it is largely tacit and shared informally. Here, we sketch out an idea for an intelligent industrial diary, building on the concepts of cognitive mimetics and human digital twins and focusing on ontology-related aspects of the system. We ask how human knowledge and knowledge of humans can be captured and operationalized to provide the necessary currency and basis for intelligent technology and its design. Our idea is derived from empirical research on the concept of a "next-generation diary" for pulp mills. The broader idea is that intelligent industrial diaries could become a key focal point for accumulating the knowledge needed for intelligent technology, thereby embodying the main ideas in cognitive mimetics.

Keywords: Digitalization, Tacit Knowledge, Intelligent Technology, Cognitive Mimetics, Industry 4.0, Industry 5.0, Technology Design, Ontologies

INTRODUCTION

Research and practice in digitalization and intelligent technology are taking place at an accelerating speed. Digitalization in industrial contexts is most often referred to as Industry 4.0. The term comes from a national initiative established in Germany after the financial crisis of 2008 and reported in 2013 (Kagermann et al. 2013). It refers to the 4th industrial revolution, which is characterized by connectivity, automation, machine learning, and real-time data. At present, the next step, Industry 5.0, is already being envisioned (Breque et al. 2021). Industry 5.0 brings a wellbeing and human-centric approach into focus, in addition to twin transition (transition to a more sustainable industry through digitalization). While technologies will become more and more sophisticated, the focus will increasingly be on human-technology systems (Paasi et al. 2021, Hollnagel & Woods 2005). This will mean that the work content and the roles of employees in industry will also change (Saari et al. 2021). Thus, how the human role in industrial processes is understood and how this understanding is operationalized are key elements of intelligent industry. It therefore makes sense to ask how our understanding of the human mind and cognition can be used in the development of intelligent industrial processes. One possible path toward this is what we have called cognitive mimetics (CM) (Saariluoma et al. 2018). The question that CM addresses is how human knowledge and knowledge of humans can be captured and operationalized to provide the necessary currency and basis for intelligent technology and its design. Here, we seek to open new directions for research through a discussion of the design of a digital industrial diary.

Problem and Conceptual Background

One of the key problems with Industry 4.0 is that the relevant systems, such as digital twins or cyber–physical systems, require knowledge to perform their functions (Ullah 2020). Currently, much of that knowledge is in the human domain; it is largely tacit and shared informally. Industrial diaries could be an ideal tool for harnessing this knowledge. However, existing diaries are generally far too informal and unstructured for use by humans who do not possess the necessary domain- and context-related knowledge, let alone by machines. This shows an epistemic gap between humans and machines. On one side of the gap are machines that are oblivious to human knowledge and human ways of thinking, acting, and interacting with technology. On the other side are humans that are only partially aware of machine (especially software) operations. The practical case provided by our research context is that of a diary with incomplete and unstructured information. We argue that this problem can – and does – extend to designing systems at the interface of human and machine operations in such a way as to achieve mutual intelligibility. Addressing this issue would be an important step toward achieving a more intelligent overall system, as envisioned in Industries 4.0 and 5.0. The problem is to design an industrial diary that is intelligent enough to act as a mediator between human and machine ways of knowing.

The term “mimetic” as it is used in technology design originates in biomimetics,

which is now a well-established approach (Lepora et al. 2013) for developing new technologies based on principles, functions, forms, and other features extracted from the biological world. Cognitive mimetics takes the core idea of biomimetics and extends it to the design of intelligent technology, with one important difference: it focuses on human information processing or cognition (for an example, see Newell & Simon 1972). However, human cognition is opaque to common sense understanding. Thus, methods, tools, and expertise are required to uncover it. This article presents one way in which CM can be used to bridge the gap between human and digital information processing. We believe that the key to achieving a good design for the diary lies in ontologies and *processes of ontological engineering* (Chandrasekaran et al. 1998, 1999). Ontological iteration turns the NGD into an intelligently interacting artifact and an embodiment of operator knowledge and thus into a kind of *human* digital twin (Saariluoma et al. 2020).

CASE STUDY: A NEXT-GENERATION DIARY

Although Industry 4.0 focused on the manufacturing industry, other industries cannot overlook the digital transformation it brought. The amount of data collected at factories and mills has increased, and sensors and related analytics with faster connections and greater computational power have become more affordable, providing essential information for both production process and maintenance (Oztemel & Gursev 2020). This affects the process industry as well. The research for this paper was conducted as part of an umbrella project, the purpose of which was to work within an ecosystem of forestry and IT companies to devise digital concepts for the forestry industry to enhance its operations within and between plants and throughout the life cycle of each plant.

Case study and findings

The case company, which has several pulp mills with advanced automation and information systems, requires – apart from technical data – human observations and tacit knowledge related to events, mainly out of the ordinary ones. To this end, it uses a digital industrial diary in which observations are reported by process operators from different departments and shift supervisors (shift workers). Each entry should include a description of the event and, if applicable, the object it refers to, as well as, where possible, a conceivable solution. The entries can be supplemented later, and comments can be added as more information is gathered. The event information entries in the diary are used on the shopfloor level by other shifts and departments in the mill for operative actions, on the management level for building a tactical situational picture, and on the back-office management level for strategic planning.

However, there are challenges related to the scarcity and uniformity (e.g., terminology, language, dialect, and extent) of the entries, which make it difficult to harmonize, analyze, and exploit the information contained in them locally, let alone

regionally or globally. Therefore, our aim is to identify ways of overcoming these challenges using novel technologies and design principles to create a system that takes into account and contributes to the capture and elicitation of tacit knowledge. The short-term objective of the NGD is to store relevant information and pass it on to production and maintenance personnel, while its long-term objective is to accumulate the tacit knowledge of the employees, combine it in a context-specific manner to other information, and process it so that information and experiences can be shared between shifts, departments, and mills and easily searched for and exploited in the future.

Insights for the NGD were gathered through semi-structured interviews with employees, ranging from operators to mill directors. In addition to the interviews, we also had access to current diary data from a period of over 2 years. In this paper, we focus on operators and shift supervisors, who are the main producers of event data for the NGD. The interviews focused on the core tasks, use, and role of the diary in people's work and sought insights into overall factors to consider and sentiments with respect to the proposed future NGD. In total, 13 operators and 5 shift supervisors were interviewed. The current diary played an important role for all interviewees, most of whom relied on it, in addition to discussions at the change of shift, to discover what had been reported since they last used it. They mentioned that it gives them an overall situational picture of the operation of the mill, or rather on the deviations. However, it is difficult and sometimes even impossible to search for more detailed information, especially over a long period, due to the heterogeneous content of diary entries, in addition to their terminology, language, dialect, and scope. Although the diary information is considered important, its use has been hindered by usability issues, the somewhat underdeveloped processes for the use of the entries and the provision of feedback, the lack of defined responsibilities, and failings in the categorization of events. The current diary supports the creation of entries in free text form and the addition of some context information (mill, process phase or department, and shift) and the enterprise resource planning (ERP) code of the device or equipment in question, although the latter is rarely used. However, many entries do not relate to specific devices (e.g., "brown dirt in the sheets," "more speed to bleaching," "acid sacks are finished"). The interviews and subsequent workshop led to the identification of 58 user needs and 23 features that interviewees would like in an NGD. The main issues with the existing diary related mainly to free text-based data entry processes, which contribute to the scarcity of entries and make it difficult to match the entries to specific areas or devices, thereby restricting its use (e.g., making it very difficult to search for similar events and exploit their solutions and documented impact information).

The following features in particular implicate ontologies:

- guidance and interaction on creating entries: making suggestions (e.g., add picture(s)/video(s)) and asking questions (e.g., What was the cause? What was the corrective measure? What was the impact of it?);

- intelligent text recognition; intelligent language/dialect translation; language

checking (suggesting corrections);

– ready-made menus for more structured information (e.g., tree-based) but few or no compulsory (code) fields;

– intelligent search by device, device type, department, and/or date (e.g., identifying similar events automatically and matching events to the same or similar devices or artifacts); integration with other systems such as process control, maintenance, analysis, and root cause tools; usage based on visual representation of the mill.

Discussion

The user needs and features outlined above all relate to the concept of ontologies, which gives us a concrete basis for discussing our design idea on a general level. An important precursor and partial basis for our discussion is the work of Chandrasekaran, Josephson, and Benjamins (Chandrasekaran et al. 1998, 1999), which makes a key distinction between knowledge of the world and of a domain on the one hand and knowledge of problem-solving on the other. We regard problem solving as one type of information processing and, in even broader terms, as an aspect of *action.* Thus, we generalize the above to a distinction between knowledge of the world and knowledge of what to do. Regarding the second aspect, knowledge of what to do, it is useful to distinguish between events and states in the mill on the one hand and actions on the other. By disentangling but relating the two, it becomes possible to represent the fact that sometimes one type of action is applicable to many situations and that many actions may in fact be applicable to a single situation. Regarding the first aspect, world knowledge, the distinction between upper ontologies and domain ontologies is crucial. The construction of upper ontologies is important for the overall organization of knowledge, but it is at the level of domain ontologies that specific content is introduced. Highly abstract representational elements, such as objects, relations, states, events, and processes (Chandrasekaran et al. 1998), which are constructed a priori, reside on the upper level. However, the main point of the diary is to act as a tool for the capture and construction of domain ontologies, which are *not* only constructed a priori by designers or programmers but also constructed by (in the present case) operators and other stakeholders at the mills through normal (and reflective) use of the diary. The point is that the empirical way in which they "carve the mill at its joints" becomes the basis for knowledge representation in the diary.

In a recent work on Human Digital Twins (Saariluoma et al. 2021), we identified a high-level structure to operator action in an experiment-oriented paper mill. The concept can also be adapted to the present context. The structure was a pattern of action categorized as *ideal, exception, and correction.* The diary, in practice, tends to be used to capture exceptions, anomalies, problems, faults, and such. In other words, when things go smoothly, there is nothing to report – or nothing specific at any rate. Ideal and exception can be used here to refer to human evaluations of the state of the system. Hence, they refer to observations and include an evaluative component.

Correction, on the other hand, refers to an action that returns the state of the system toward the ideal. Most entries in the diary seem to reflect this ontology in that they typically *describe* or *anticipate* some non-ideal state or property of the system and sometimes explicitly (at other times, tacitly) add a corrective action (or request one).

Another general consideration is that, logically, states or events and actions form chains and networks, which the NGD should be able to accommodate. For example, a non-ideal state in one part of the mill necessitates an action that has effects beyond the target of the corrective action. For example, a fault may result in two actions, running the machinery at a low speed and subsequently performing a repair, both of which may have the effect of preventing production targets from being met. In other words, events and states have causes (some of which may be actions), and actions have *reasons* and effects. It should be noted that reasons and anticipated effects are clearly within the cognitive domain of the mill personnel and are only partially described in the physical-causal ontologies of, for example, digital twins. In an abstract sense, this unfolding of interlinked events, states, causes, actions, reasons, and effects describes what is occurring at the mill on the level of a joint cognitive system (Hollnagel & Woods 2005). These concepts also introduce time into the system, calling for the representation of past, present, and future in the ontology. This provides us with a reasonable upper-level ontology that has both cognitive tractability and much room for specification. Analyzing its applicability is an empirical project for future work and indeed part of the operational principles of the NGD as we envision it. For now, the proposed ontology allows us to conceptualize some aspects of this system at the interface between the mill and the humans who work there.

On one level, we have a general ontology, and on another, we have the entries. The general ontology is not a domain ontology, which is the target of our diary. Thus, a mediating level is needed, which here we call *patterns*. Patterns were first introduced by Alexander (1977) in architecture and have since been adopted in software design (Buschmann et al. 2007). Patterns are essentially intended to describe, in a general, reusable way, recurring problems and respective solutions. The key point is that a well-designed pattern ontology could be used to record recurring events at the mill and their implications and solutions. Combining these patterns (ontologies) with other systems, such as ERP or digital twins, would enable us to construct links based on particularities but without loss of generality at the diary level. Such patterns, and their interconnections, could provide a robust basis for computational reasoning, as well as human communication. The power of patterns in their original context of *design* is that they are mimetic of a certain type of human information processing, namely problem-solving, while also being non-restrictive enough to match a variety of circumstances. Initially, the patterns should be created by designers based on the empirical needs of the users and the properties of existing entries. However, they should be subject to revision when needed, and allowances should be made for the creation of new patterns when existing patterns fail to naturally capture an event/state or action. An ontologically organized library of patterns would allow for the creation of substance-rich but easy-to-input entries into the diary. The more developed the

library, the ontology, and the associated technologies (such as language recognition, visualization, and predictive input), the quicker and easier it would be to enter events into the diary.

CONCLUSION

This paper opens avenues for future research. We have sketched an upper-level ontology that is subject to and open for revision and specification. On the level of entries, we should look for empirical patterns in terms of how they fit with the ontology. It should be noted that ontologies in our thinking are organized into levels with at least an upper ontology, an ontology of events/states and actions, and several ontologies that can capture types of events/states and actions (i.e., patterns). There should be no discrepancies between these levels: the patterns should reflect the reality of the mill and of the operators, the entries should reflect the patterns, and the ontology should accommodate the patterns. The aspects should therefore *converge.* Importantly, the most important level is the pattern level, which is empirical. The question of human–technology interaction whereby patterns and associations among them (or their elements) are created and used merits separate treatment in a future article.

The approach seems promising for establishing the basis for an intelligent diary that is mimetic with respect to empirical information processes *and* events in pulp mill environments. While these remarks are promissory, nothing in them seems technically or theoretically unfeasible. For example, language technology and ontological techniques have advanced significantly, which we believe is an enabling factor for the capture of empirical domain ontologies through the concept of pattern. Then, through the concept of directed associations (of various types), these can be transformed into a network of local chains of events.

One final remark must be made. In CM, it is one issue to analyze empirically how people process information and another to analyze how they should process it. Thus, designers can and should enrich empirical results and seek to design an ideal ontology. The design of ideal ontologies can be seen as a form of conceptual engineering. Thus, empirical work and conceptual engineering appear to be important components in designing human digital twins with sense-making mimetic models of human information processing.

ACKNOWLEDGMENTS

This work is funded by the SEED project (seedecosystem.fi). We are grateful to our case company and the companies and organizations on whose collaborative work in the insights phase this article is founded.

REFERENCES

Alexander, C. (1977). *A Pattern Language: Towns, Buildings, Construction*. Oxford: Oxford University Press.

Breque, M., De Nul, L., Petridis, A. (2021). "Industry 5.0: Towards a Sustainable, Human-Centric and Resilient European Industry." Luxembourg, LU: European Commission, Directorate-General for Research and Innovation, https://ec.europa.eu/info/research-and-innovation/research-area/industrial-research-and-innovation/industry-50_en

Buschmann, F., Henney, K., Schmidt, D. C. (2007). Past, Present, and Future Trends in Software Patterns. *IEEE Softw*. 24(4), pp. 31-37.

Chandrasekaran, B., Josephson, J. R., Benjamins, V. R. (1998). The Ontology of Tasks and Methods. In: *11th Workshop on Knowledge Acquisition, Modeling and Management (KAW'98)*. Banff, Canada.

Chandrasekaran, B., Josephson, J. R., Benjamins, V. R. (1999). What Are Ontologies, and Why Do We Need Them? *IEEE Intell. Syst. Their Appl.* 14(1), pp. 20-26.

Hollnagel, E. and Woods, D. D. (2005). *Joint Cognitive Systems: Foundations of Cognitive Systems Engineering*. Boca Raton, FL: CRC press.

Kagermann, H., Wahlster, W., Helbig, J. (2013). Securing the Future of German Manufacturing Industry: Recommendations for Implementing the Strategic Initiative INDUSTRIE 4.0. Final Report of the Industrie 4.0 Working Group.

Lepora, N.F., Verschure, P., Prescott, T.J. (2013). The State of the Art in Biomimetics. *Bioinspir. Biomim.* 8, doi:10.1088/1748-3182/8/1/013001.

Newell, A. and Simon, H.A. (1972). *Human Problem Solving*. Oxford: Prentice-Hall.

Oztemel, E. and Gursev, S. (2020). Literature Review of Industry 4.0 and Related Technologies. *J. Intell. Manuf.* 31, pp. 127-182. https://doi.org/10.1007/s10845-018-1433-8.

Paasi, J., Nieminen, H., Kurki, S., Apilo, T., Martins, J. T., Malinen, S., Ahola, A., Salminen, K. (2021). Sustainable Industry X: Kohti suomalaista teollisuusvisiota ja -agendaa 2030. VTT Technical Research Centre of Finland. VTT Technology No. 389, https://doi.org/10.32040/2242-122X.2021.T389.

Saari, L., Kuusisto, O., Häikiö, J. (2021). ManuMaturity: A Maturity Tool for Manufacturing Companies to Reach Beyond Industry 4.0. VTT Technical Research Centre of Finland

Saariluoma, P., Cañas, J., Karvonen, A. (2020, August). Human Digital Twins and Cognitive Mimetic. In: *International Conference on Human Interaction and Emerging Technologies*, pp. 97-102. Springer, Cham.

Saariluoma, P., Karvonen A., Sorsamäki, L. (2021). Human Digital Twins in Acquiring Information About Human Mental Processes for Cognitive Mimetics. In: *The 31st International Conference on Information Modelling and Knowledge Bases (EJC 2021)*. Hamburg, Germany.

Saariluoma, P., Kujala, T., Karvonen, A., Ahonen M. (2018). Cognitive Mimetics - Main Ideas. In: *Proceedings of the International Conference on Artificial Intelligence (ICAI)*, pp. 202-206. The Steering Committee of the World Congress in Computer Science, Computer Engineering and Applied Computing (WorldComp)

Ullah, A. S. (2020). What is knowledge in Industry 4.0?. *Eng. Rep.* 2(8), DOI: 10.1002/eng2.12217.