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Human digital twins in interaction design – from abstract to concrete

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ABSTRACT

Human digital twins are a promising tool for designers. Digital twins have long served as models of technical and cyber-physical processes. Human digital twins take such models and add interactions with human users. Thus, human digital twin models enable technology designers to model people interacting with technical artefacts. The conceptual structures of such models present numerous open conceptual problems. To clarify this issue, we designed an interaction model for such general abstract machines as Minsky's M-Machine. The abstract conceptual structure of this machine allows us to consider at a general level the interaction processes involved in constructing models of human digital twins. The M-Machine model could help designers construct solutions for concrete human digital twins for human–technology interaction processes.

CCS CONCEPTS

• **Human-centered computing** → Human computer interaction (HCI); HCI design and evaluation methods; User models; Interaction design; Interaction design process and methods; User centered design; Human computer interaction (HCI); HCI theory, concepts and models.

KEYWORDS

Human digital twins, Interaction modelling, Design science, Cognitive mimetics

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1 INTRODUCTION

Society 5.0 and its industrial component, industry 5.0 programs, are changing technology design thinking [5] [8] [36]. The ultimate motivation for changing perspective is the emergence of intelligent technologies and artificial intelligence (AI). These new technologies can carry out tasks that had earlier been performed by people [17] [22]. The efficiency of emerging intelligent technologies makes it necessary to shift to more holistic design thinking in which the focus will be on what people do with technologies.

Instead of designing mere technical artifacts, the goal of emerging technology design is to shape how people live and work [8] [26]. For example, choosing the best form of and material for pistons is still a vital problem in car design, but understanding how people live in megacities and use cars in everyday life is becoming an increasingly more important design problem. Designers must think about how people interact with new, intelligent technical artifacts and not only create cyber-physical objects. The focus of technology design in society 5.0 is as much on creating new social actions as on fashioning new technical artefacts. Thus, the design of the properties of artifacts, such as algorithms, will remain an important issue in designing intelligent technologies—but it provides only a part of the challenge. Human digital twins and cognitive mimetics are a set of bridge concepts and methods that allow for an integration of the internal properties of artifacts, their environments, and the human actions they support.

Artifact-oriented thinking has dominated machine technology and AI design research [22] [33]. However, the artifactual orientation has led to confusion in the ICT field because the role of humans has been underestimated [22] [24]. A typical example is SMS. It was designed as early as 1984 but adopted for public use only years later, in early 1990, by mobile phone companies. Designers had not found the ultimate use for the idea, as the design culture did not support holistic thinking [9] [31]. Later, the SMS model led technology providers to invest their design efforts in the expensive and futile WAP paradigm, which could not work due to poor usability [23] and poorly designed message length.

History thus suggests that artifact-oriented design thinking may lead to many *cul-de-sacs* that could have been avoided by paying more attention to actual usage. Perhaps understanding the problems of users and their memory limitations would have called designers' attention to the importance of graphic interface technology, as was standard in the world of personal computers, if only design thinking had been more holistic. Consequently, holistic technology design thinking has its advantages, and emerging intelligent technologies make it important. Artifact design is a necessary part of technology design thinking, but it is hardly sufficient in the era of emerging intelligent society.

However, the above example, which illustrates the problems with a technology-oriented way of thinking, invites one to ask what the form of future technology design should be. One can ask what the conceptual structure of future intelligent interaction design could be like. Here, we shall focus on two important concepts: cognitive mimetics and human digital twins [14] [28] [25]. These concepts are intimately interconnected and, together, could provide a tool for developing future design thinking.

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2 COGNITIVE MIMETICS

Intelligence can be understood as adaptive, sense-making information processing, and the best example in nature of this kind of process is human information processing [32]. Intelligence is the capacity to organize information in a sense-making manner. For example, when solving problems, people are able to transform an initial information state into a solution [20]. AI systems can also solve problems [20] [22]. A practical example was Turing's work on deciphering German naval codes during World War Two [10].

As the human mind is the best example of intelligent information processing, it is natural to ask how one could benefit from knowledge of the human mind when designing intelligent technological systems. Presumably, the first model of this kind was the Turing machine [32]. While it was essentially a device used by Turing to show that the meta-mathematical decision problem was unsolvable, it was also a model of *human*–computer information processing. Later, the model was generalized in the works of Herbert Simon, his collaborators, and many other researchers [20] [22]. A tradition of psychological models of the human mind was developed [1] [19].

There is just a brief step from modelling human thinking to designing intelligent processes. If there is a technical artifact, such as a ship, that can move from one harbor (A) to another (B), there must be an information process that makes it possible to sail from A to B. Following Turing's [32] original design logic, it is possible to design an information processing system that can sail a ship from harbor A to B. Thus, the system could imitate human information processes if only it could be opened, explicated, and transformed into a form suitable for artificial systems. Thus, it must be implemented—i.e., designed. The two sides of the equation, research and design, should be able to enter into a constructive co-design process to realize the core idea of cognitive mimetics. The core idea is simple: just as, in biomimetics [34], designers have imitated biological structures and mechanisms to create novel technological solutions, in designing intelligent technology, we can turn towards human cognition as a source of solutions [14] [28]. The distinguishing difference is simply in the perspective adopted with respect to the source: cognitive mimetics analyzes information processes (and contents) instead of biological structures or mechanisms. For this reason, cognitive mimetics is a good tool for hybrid AI thinking.

3 HUMAN DIGITAL TWINS

Cognitive mimetics is a model of a design process for intelligent technologies. However, a mere process is not sufficient. It is also essential to construct models of intelligent action in which people and machines process information as systems [11]. Human digital twins provide a conceptual framework for operationalizing cognitive mimetic research and design. The main goal of cognitive mimetics is to investigate what happens in the human mind and to use that as a central element in the design of intelligent technology.

Digital twins (DT) are computational models of machine and other mechanical or cyber-physical processes that are typically connected to their reference systems through dataflows [12]. They can be used to develop new technological solutions. Instead of building physical-scale or miniature models, designers can study the properties and behaviors of their potential solution alternative using computational models. Furthermore, DTs can be used as a basis for automation and other intelligent control methods. They can also be used in studying and comparing possible alternative solution models. Thus, digital twins are practical tools for designers to use in cyber-physical systems.

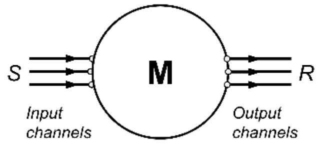

Figure 1: M-Machine, adapted from [17].

However, the cyber-physical world operates in causally organized, physical or mathematically determined data realms. The human mind follows different kinds of principles. While in cyber-physical systems, causes precede effects, the human mind operates intentionally, so that it pursues goals to be reached later [3] [35]. Human systems are intentional. Human minds, as mental systems, have information content that is about something—for example, a representation or state of an ideal situation. Thus, digital models of human action or HDTs should be built on different modelling types from cyber-physical systems but also harmonize with them. If similar benefits are to be gained from DTs, the models should mimic human thought and action to a degree fit for purpose. Thus, cognitive mimetics and HDTs are a natural pair from this perspective. In practice, human actions should be harmonized in models with the actions of technical artifacts, but thanks to differences in the principles that human minds follow, it is essential to use paradigms that best fit the mental operations, such as perception, attention, language, and thinking [1]. Such models have been developed, e.g., within cognitive psychology over the years, beginning with Turing machines [32], TOTE [16], and physical symbol systems [21], as well as GOMS- [19] and ACT-R-like [1] architectures. Moreover, additional kinds of models have been built on neural networks [13] [15] [30]. In this paper, we suggest an additional model for human actions in process control called IEC: ideal, exception, and correction [27].

3.1 The M-Machine

Our target artifacts have been presented here in accordance with the M-machine (the Minsky machine) proposed by Marvin Minsky [17, p. 13–14] (Figure 1).

Minsky [17] claimed that the M-Machine is a general model of any machine, and we agree with him—for the time being, at least. Consequently, we designed an HDT for interacting with an M-Machine to construct a conceptual HDT for general human–machine control-type interactions.

In this conceptual model, presented in Figure 2, the technical artefact is the M-Machine. The user interacts with the M-Machine by means of a human interaction point (HIP), and finally, U stands for a user. We assume that any technical artifact designed for process control has this same abstract structure. It is thus a general model for constructing

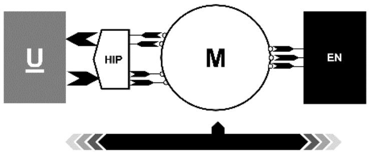

Figure 2: Human digital twin for an M–Machine. U = user or operator, HIP = human interaction point, M = machine, and EN = (action) environment.

HDTs for control tasks. To clarify our way of thinking further, the three elements of the model—the M-Machine, HIP, and user—shall be discussed more in detail.

Minsky [17] constructed the M-Machine as an abstract model of any machine (see Figure 2). It has a set of input information types controlling the analysis of task and situation information. It has also a set of output channels that manipulate objects of action following the instructions given in the input information. The M-Machine offers a set of processes to transform target environments or objects of industrial action into a desired end state. Human intentions define ideals for process states. In addition to input processes, the M-Machine has a set of output processes.

Minsky's [17] M-Machine is a black box. However, it makes sense to define a set of internal processes that make it possible to manipulate the object of action effectively. Input actions manipulate these internal processes, and one can thereby explain why definite input operations make sense. Internal states also make it possible to automatically or autonomously modify M-Machine processes.

The M-Machine is a general and abstract model of the machine component of a HDT. As such, it cannot be a model for any industrial process. It must be interpreted or concretized by defining all the process-relevant inputs, all the relevant outputs, and the structures and operations of the internal processes. In this way, the M-Machine becomes a model for a definable machine process.

A paper machine, for example, has controls that enable users to steer the behavior of this often almost one-hundred-meter-long machine and its internal processes. The paper machine involves complicated processes. For example, wet pulp that is over 90% water is transformed at a speed of over 90 km/hour into 11-meter-wide sheets with a 2/100-millimeter tolerance [29]. The goal is thus to produce paper sheets for different uses. The control systems enable people to secure the smooth operation of this action.

The M-Machine can, by means of interpretation—i.e., defining input variables, output variables, and internal processes—be modified to model any machine. Thus, it can become a model of any control-dominated HDT. The core process is the given interpretation of the key elements, which concretizes the machine component of the HDT.

3.2 HIP

People operate machines, and they are involved with the processes therein. The degree of involvement may vary. A thermostat controlling a room's temperature can be fully automatized so that people only set it but do not touch it for a decade. Nevertheless, the thermostat is operated by people. Of course, sometimes, as in car driving, people are very much in the loop and constantly steer the process. Human involvement can vary between these extremes. The points and the actions through which people are involved in the processes of an M-Machine can be called human interaction points (HIPs).

An HIP is not a model of a user interface though interface is an essential part of HIP. It rather describes how an operator can and should be involved in a machine's processes, i.e., what happens to machine process when people control it in some way. HIP is thus a description of action instead of user interface. Moreover, an HIP should not be confused with the concept of a "touchpoint" used in marketing-oriented customer experience research and management, where a touchpoint refers to any type of stimulus—such as the interaction with a product, service, atmosphere, or communicative tool or instrument—that creates a subjective experience in its user [37].

In paper production, the operators must walk several hundred meters to take a liquid sample and analyze it. HIPs describe such operations. HIPs also entail controls and meters. Importantly, the HIP is a framework for defining possible operations with respect to the M-Machine and a schema upon which actual operations can be populated. All actions are thus selections from this space of possibilities.

HIPs define the actions people take when they operate a definite technology, and for this reason, they must be concretized application-wise. Defining HIPs makes HDTs, for their part, concrete. All machines have their HIPs, but the nature of the concrete operative actions in an HIP depend on the particular technology. These actions are made possible by controls and meters in the user interface.

3.3 Describing users of HDTs

Finally, the last component of an HDT is the user or operator. Therefore, it makes sense to include the properties of users in any HDT. Minsky [17] did not have a model of the user in his M-Machine, but it still makes sense to think what kind of properties are needed in describing human users. The problem is complicated, as the research in human interactions with technology has opened up a vast field of important properties [4]. Here, we shall focus on describing the conceptual structure of the user in the context of constructing HDTs.

The starting point of understanding users of HDTs is action—what people intend to do with an artifact, and why they use this technology. However, action can be considered from different perspectives. Here, we call attention to two major perspectives on user modelling in HDTs. The first can be characterized as intentional, and it defines what people are doing. What is the end state they intend to reach? The second perspective is to answer the question of whether people can do what they intend. The latter is basically a causal view, and its analysis is based on human beings' limited information processing capacity. It can be used to analyze, explain, and design human errors.

The first view defined by the goals of the action is intentional. It explicates why it is good to do what people are doing and what people hope to achieve in their lives by performing the given actions. Paper machine investors and industrialists hope to make good paper to be used by clients for various purposes that are important in their lives. A secondary motivation may be to make profit, but this is not the main intention of the industry.

A designer needs to create both intentional and causal descriptions of the user. Intentional descriptions answer the question, what does a person do? What does a person aim for when using a machine? Typically, intentionality can be investigated with techniques such as task analysis or event trees [26]. It is also necessary to differentiate life action goals and user goals. For example, a life action goal might be wanting to fix a hole in a tooth, whereas a user goal could be knowing how to use a tooth drill. Causal description asks, can a person use a technology, and how? Does a person understand a technology, and how? User knowledge describes what the person (user) has learned about the operation of the machine.

An alternative perspective on machine use is opened up by the question, can people use technology? Human information processing is limited. We can attend to one issue at a time or remember 4–7 new chunks in our working memories. Secondary tasks also illustrate the limits of human working memory [2]. Two visual memory tasks, for example, interfere with each other. Thus, the way people have to use their capacities may affect the correctness of the performance.

When modelling human users, designers should thus explicate the information contents required in both planning and carrying out the task [18]. They should also investigate the limits of the information processing systems and support attention and memory in processing task-relevant information. The model of the user in HDTs describes human intentions (e.g., operative intentions, or reasons for carrying out some definite action, and life-level intentions, such as reasons for being involved in the paper business). In the case of any machine, such as an M-Machine, people have different roles. They can be operators, management personnel, or owners. The notion of the user is designed to cover all these roles.

Because all the defining parameters in M-Machine HDTs are abstract, the HDT model presented can be applied to very different types of machines whose operations people intend to control. Our approach to designing HDTs is based on the idea that HDTs are abstractly analogous. By creating abstract HDTs, it is possible to study HDT design problems on a higher level and by bounding abstract variables to concrete processes.

3.4 Ideal, exception, and correction

HDTs are tools for designers. The spectrum of technology-supported human actions that can be modelled by HDTs is wide, and therefore the palette of possible HDTs and their types also varies extensively. The IEC model was based on modelling the work of operators in the paper industry [27].

The original IEC model was specific. Therefore, it made sense to ask how to generalize the model, and one way to do so is to construct an IEC model for people interacting with some general technical artifact. This kind of HDT is abstract, but it is applicable to a large number of concrete processes with the same control-based action logic [27].

The IEC model emerged as a consequence of empirical investigation into the thoughts and actions of operators in an experimental paper mill in Finland. As a result of analyzing the collected think-aloud protocols and interviews, a pattern emerged (see [17] for details), illustrated in Figure 3. The operators' thinking on a higher level apparently takes the form of IEC. They see how things are straying from the path they desire, and consequently, they understand that they must do something to prevent things from reaching that state. They compare information on the present state of the process with the idea of determining a way to reach an ideal state.

Based on these protocols, we can see the basic logic of the operators' thoughts and actions. They have an ideal state in their minds. What that ideal state is depends on a number of issues, such as the quality of paper they are producing, the raw materials they have at their disposal, and the state of the production process. Operators encode the present state of the technical process and register exceptions from the ideal. They can register deviations from the ideal state by comparing the present state with the expected ideal. They can, furthermore, anticipate deviations based on their extensive knowledge. Finally, operators have in their minds a list of possible corrective actions, which they apply to bring the process to the ideal state.

Based on this, we developed a small model for operator information processing called IEC_0.81. IEC_081 assumes, based on empirical research, that the operators' thinking has an ideal–exception–correction (IEC) loop. Operators observe the behavior of the machine process by means of measurement instruments and visual contact in the control room. Information is also passed on "from the field" by other operators who work physically close to the paper machine. When they observe an unexpected state of the process (or rather a deviation from the ideal), they take appropriate actions, following the models of their anticipated effects.

The model is based on the idea that all HIPs can be defined. The point entails a set of observation values (OVs) and a set of possible actions (PAs). Since the machines are closed and defined systems, they have for each HIP a limited set of OVs and PAs. All possible human actions of involvement in the ongoing machine process can be thus defined in terms of HIPs, OVs, and PAs.

The IEC_081 model itself is very simple, but it can still give us an idea of the role of HDT models in information collection. The model provides an interpretation of one possible solution to the problem of how human information processes and their contents operate in controlling paper machines. Similar simulation process can naturally be made by some traditional model of human mind such as ACT-R [1] or GOMS [19]. The reason for choosing IEC_81 was that it explicitly expresses the structure of human involvement to controlling machines and thus follows how people control machines.

IEC_081 does not yet provide a detailed description of ideal processes and states or corrective actions. It does not yet offer precise information about operator actions. Nevertheless, the model can be developed further by studying how operators carry out their actions in different situations. Thus, the model can very effectively aid the direction of information collection on operators' mental contents. The model also enables researchers to test the logic of their interpretations of data. If simulations work, this suggests that the interpretations do not have a problem in their formal structures. If simulations do not work, it means that the interpretations must be reanalyzed. Internally contradictory models are impossible, so simulation makes it possible to perform a self-corrective analysis and interpretation of data on mental contents.

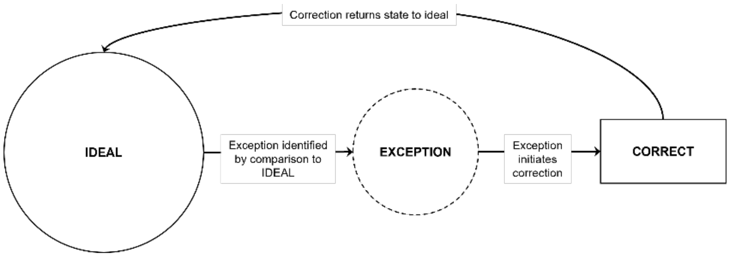

Figure 3: Ideal-Exception-Correction model ([27], p. 172).

Thus, the IEC model has the function of guiding research. If it reaches a final state, it becomes a HDT in the sense that it is both a model of operator action and a reflection of their mental contents. Essentially, this would be a potential automatic controller, or a basis for it, that is cognitively mimetic of operators' actions and thoughts. This simple basis can, however, be taken in many directions.

4 CONCLUSIONS – FROM ABSTRACT TO CONCRETE

HDTs are conceptual, computational models of people using technologies to achieve their action goals in life. HDTs are constructed to analyze and explicate features of human interaction involving technical artifacts to reach their operation-specific and broader life goals [26]. They are models that designers can use in developing new technological solutions. HDT models can be used to assess alternative solutions. Modelling interaction problems at the generalized level of designing interaction models for M-Machine-like, abstract-but-general conceptual models is a tool in the HDT designer's toolbox.

Abstract HDT models, such as that of the M-Machine, have their uses in developing design models. HDT designs can be organized to proceed from abstract and general models to concrete cases. General user parameters, such as user intentions, can be defined in a process-specific manner. At the same time, one can specify both internal machine functions and human operative functions. Thus, moving from abstraction to concrete cases makes working with HDTs easier and easier to organize. This allows the generalization of HDTs to a large class of design problems. As the IEC model can be interpreted on various levels of sophistication based on the generality and simplicity of the control structure, from simple lookup tables to richer structures of intentional and representation modelling, it provides a holistic basis for the design of intelligent technology.

In this compact context, we have omitted discussion of mental architectures. As noted above, there are numerous such architectures to be found in cognitive–psychological and cognitive–scientific literature. They make it easier to study the human preconditions of HDT modelling and design. For example, one can find advanced information on processing limitations, such as working memory models or the expertise and skill-specific properties of users' minds.

One can study semantic networks as systems in the form of controlling attentional spotlights or limitations in expertise. It is also possible to use mental model theories of different kinds to describe what users should do, what they can do, and what they should learn to be able to use complicated technological systems effectively. HDT modelling is a practical tool for working with such design problems.

The cognitive psychology of human information processing provides many tools for HDT design thinking. Architectural models such as ACT-R or GOMS, which entail descriptions of important human processing capacities and limitations, can be helpful in clarifying mental architectures to design intelligent technologies [1] [19]. By modelling the mind, one can gain a better idea of how people work now, how they should work, and how technology designers could improve tools to make work processes faster, easier, and more reliable.

IEC is an example of an HDT model. It is intended to assist in working by modelling people in process control tasks [27]. In this paper, we have illustrated how one can construct a very abstract IEC and concretize it to model individual interaction processes. The method of using abstract engines as platforms for modelling concrete processes is one possible model for how to operate with HDTs.

HDTs can be the framework that captures actions and, over time, learns to act increasingly autonomously. Human operators can simply choose to capture an activity like a macro, and the episodic structure apparent in many contexts can be automated from a human perspective. The adaptive intentionality in human action can thus be abstracted bit by bit to higher orders of actions so that machine operations will not be strange, alien processes, but recognizably human ones. This will put human actions in the future intelligent society in the place they belong—namely, as conductors of intricate machine intelligence with human roots.

HDTs provide a good tool for conceptual engineering when working towards holistic design processes in which designers focus as much on human actions and the ways people live as they do on artifacts [6] [7]. This is needed in transforming technology design from artifact design into the construction of new kinds of society.

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