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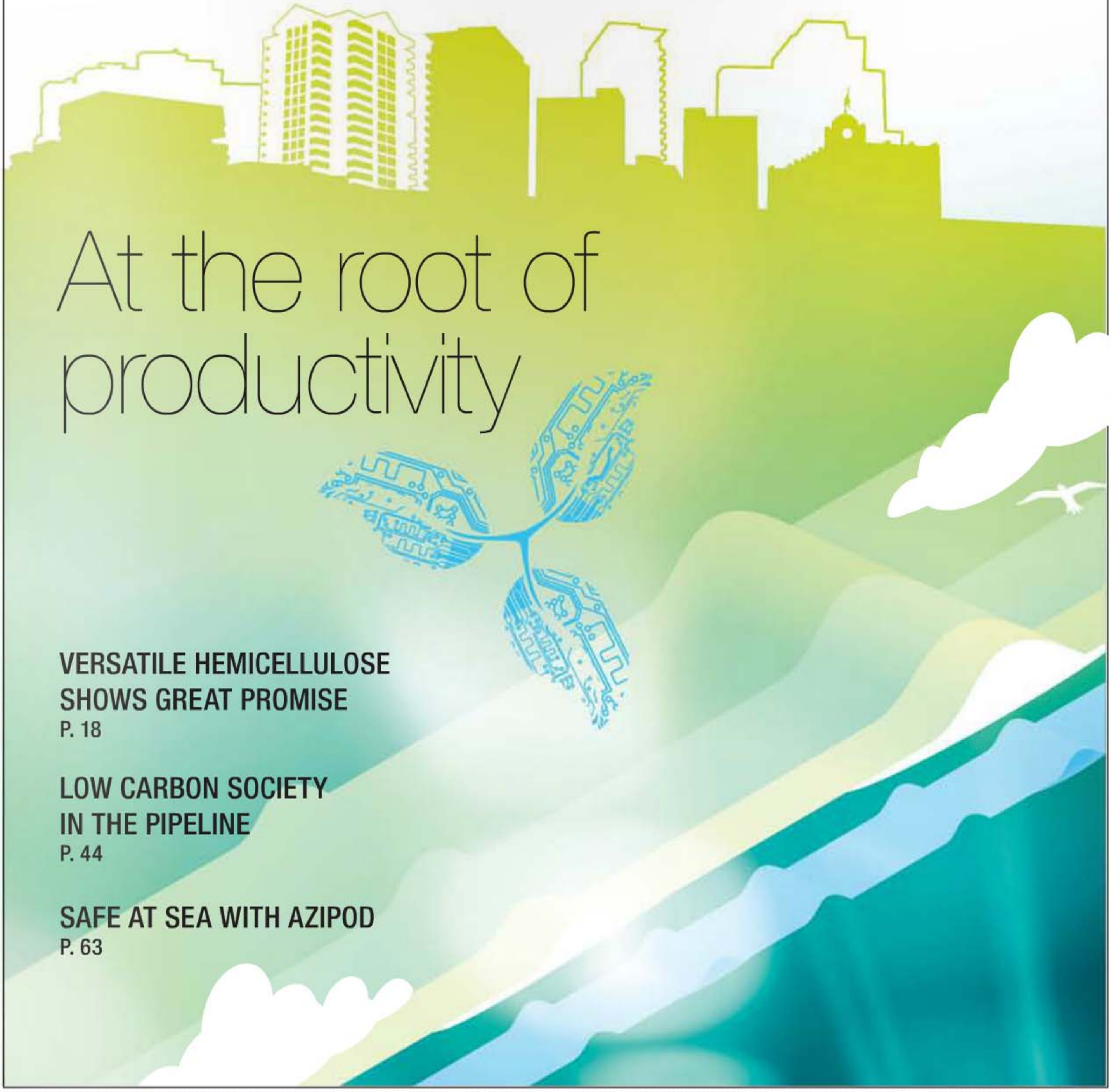

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SCIENCE

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Text: Boris Krassi & Sauli Kiviranta

The unity of human and machine

Virtual and augmented reality helps to leverage the strongest human abilities for creating better human-machine systems.

The history of humanity demonstrates the ever increasing variety and complexity of human-machine systems. The first men grabbing a stone axe, Columbus setting sail towards the New World, Neil Armstrong landing on the Moon, and millions of commuters driving their cars, are all examples of human-machine systems.

These systems are defined as the unity of human and machine working together towards a common goal, be it hunting a mammoth, crossing the ocean, landing on the Moon or reaching home safely.

Together, the human and the machine form an organism in which neither part is able to reach the common goal alone, and neither is more important than the other. This mirrors the human body's reliance on both brain and heart – the body's goal of survival is reached only when both organs work together.

Two streams of thought

Human-machine systems are deeply rooted in the history and structure of civilisation. Discussion on the interrelations of human and machine (society and technology) has been going on for a very long time, culminating in the 20th century with the conceptual debate between two streams of thought.

The first stream emphasised the human and its unique abilities, and is represented, for example, by Frankl's "Man's search for meaning" [1], Vernadsky's works on noosphere [2] – 'the sphere of human thought', and Wiener's "The human use of human beings" [3].

The second stream sought global political and financial superiority largely supported by technological means. This is represented by a whole spectrum of phenomena, from the bombing of Hiroshima through to the exploitation of mass media to manipulate public consciousness.

Even today there is a belief that war boosts technological progress, which in turn is thought to be good for humanity. However, little attention is paid to the massive and irreversible loss of human potential, and war's catastrophic effect on the development of humanity.

Another example is that the present attention to environmental, social and economic sustainability [4] often fails to consider the human potential for severing the link between a nation's wealth and its energy consumption.

> Heuristic control helps to tackle unfamiliar situations.

Rather, social sustainability is sometimes reduced to a mechanistic conclusion, such as "the only way we can preserve and nurture other and more precious freedoms is by relinquishing the freedom to breed" [5].

Another modern trend is global outsourcing and offshoring, perceived as a strategic problem by the Western world. But the actual problem is a failure to recognise offshoring as a natural phenomenon that will exist while ever there is a gradient in labour cost. Rather than resisting it, we should instead recognise and support the value of knowledge and skills as a prime asset of domestic industry.

Human-machine systems: cybernetics or ergonomics?

The controversy surrounding technological developments during and after World War II prompted a wide investigation into the distribution of functions between machine and human. Study of the analogies of "control and communication in the animal and the machine" led to the rise of cybernetics [6] and general systems theory [7].

The science of ergonomics was developed at the same time, aiming to understand and define the function of the human operator, initially in aerospace, automobile and computer technology applications.

As defined by the International Ergonomics Association, "ergonomics (or human factors) is the scientific discipline concerned with the understanding of the interactions among humans and other elements of a system, and the profession that applies theoretical principles, data and methods to design in order to optimise human wellbeing and overall system performance" [8].

Similarly, the object of human-machine systems is the joint function of human and machine as a system, a single organism; the goal is the understanding and design of better human-machine systems, i.e. systems that fit better for reaching their goals.

Whether human-machine systems can be considered as a synthesis of cybernetics and ergonomics, or simply as a branch of ergonomics, might well be the subject of debate, especially in the light of a wider definition of ergonomics in the context of "purposeful interacting socio-technical systems" [9].

However, the cybernetic focus on "efficiency of action" [10] that treats the human and the machine part equally, the wide application of cross-disciplinary analogies, and the involvement of such system-theoretical concepts as goals, system effect, information, communication and feedback, are rarely found in ergonomics.

The strength of the human

A good example of a human-machine system is the cargo ship. The primary goal of the system is to deliver the cargo. The system has a number of elements – the ship, the crew, the captain – that work together to reach the primary system goal.

The main function of the captain is to exercise heuristic control. Unlike lower levels of control that are characterised by one goal (e.g. a hand tool) or several (e.g. a reprogrammable computer), with limited freedom and considerable certainty in the means of achieving these goals, heuristic control is defined by a large variety of goals and a lack of formal algorithms of how they might be achieved (e.g. the captain during the storm) [11]. In other words, heuristic control helps to tackle unfamiliar situations, and relies on an extensive use of mental models, images and analogies.

So, while the captain is at the top of the control hierarchy, and his ability to exercise heuristic control is maximally exploited in the system design, there is no emphasis as such on his "wellbeing" or "user-centricity" unless they happen to contribute to the primary system goal. The same applies to CEOs or state leaders – it is all about goal-centricity rather than human-centricity or luxury.

Most importantly, the element at the top of the control hierarchy of the human-machine system should be able to exercise heuristic control. In principle, this would apply as much to a group of people as to a supercomputer, but today's technology is still so primitive that only the human is capable of performing heuristic control.

Human and machine: understanding the differences

Common to ergonomics and human-machine systems is the attempt to understand the abilities and limitations of the human. To clarify this, we must lay out the principal differences between human and machine, at least from the engineering point of view.

When designing a human-machine system, the engineer must keep in mind that the human part and the machine are described in different terms, and that traditional engineering models are inadequate when it comes to representing the human.

First of all, the human has considerable physical variety. We can be tall or short, slim or full-bodied, young or old, male or female, sporty or unfit, energetic or tired, and so on.

Secondly, the human can learn, while any activity carries an imprint of personality, and people naturally take different roles in a team.

Thirdly, the human holds so-called tacit knowledge, i.e. knowledge deeply rooted in one's mental model that cannot easily be expressed explicitly, for example, in writing. "We know more than we can tell" [12] is a famous expression about tacit knowledge.

Fourthly, the human can exercise heuristic control, which was introduced above.

While we cannot discuss all these differences in this article, the bottom line is that any variability and uncertainty in machines is incomparable to the variability and uncertainty in humans.

We do not claim that the machine is always simpler than the human. But while the engineers try to avoid or limit uncertainty in the machine, the human remains inherently variable and uncertain. The human should not be reduced to a mere resource, a person-hour, a record in a database, or a kinematic skeleton model.

In this respect, engineering models and design methods that are suitable for machines fail to represent the human or to design human work. Thus, according to a study at Volvo [13], only 45% (57 out of 126 cases) of the evaluations based on the digital human model simulation correctly predicted the ergonomic condition of the corresponding real tasks. There is obviously room for improvement.

> Only the human is able to make decisions in entirely unfamiliar situations.

Participatory approach

Sometimes engineers perceive the human and human work as a problem. This is not right. The human is simply different from the machine and cannot be handled in the same way.

A general solution to this difference is sought through a participatory approach [14]. This engages various specialists – from engineers and managers to workers and operators – to understand how human work is actually done "by examples" and to use the tacit knowledge of the participants in analysis and design of the human-machine systems.

The participatory sessions are not necessarily collocated. These can be distributed in time and space, and based on an artificial collaborative environment. The recent trends are open innovation, co-creation, crowdsourcing and even do-it-yourself [15] – all taking advantage of the knowledge and creativity of the clients and end-users.

The power of the image

The fact that humans carry a lot of knowledge about their own work has two important consequences.

Firstly, no knowledge management strategy can be reduced entirely to technological means. Knowledge understood as an "organisation's intellectual assets" [16] includes not only databases, means of knowledge articulation, and retrieval, but primarily the people themselves. As a result, frequent personnel changes, layoffs, and massive offshoring diminish an organisation's intellectual assets in exchange for short-term financial benefit.

Secondly, the organisational knowledge creation process must be established, "making available and amplifying knowledge created by individuals as well as crystallising and connecting it to an organisation's knowledge system" [17]. This process has four modalities of bi-directional tacit-explicit knowledge conversion [18].

The first modality is externalisation (tacit-to-explicit): expressing oneself to others. In fact, this is a process of extracting an external image – a metaphor – of the object or situation from one's mental model [19].

The second modality is internalisation (explicit-to-tacit): understanding what others express – the process of linking the external image to one's mental model.

The third modality is socialisation (tacit-to-tacit): interacting with others on the 'do-it-as-I-do-it' principle.

The fourth modality is combination (explicit-to-explicit): making inferences on the external images, e.g. by means of semantic web technologies.

All these four modalities require the extraction, communication, and linking of the external images.

Here is an example of a possible knowledge creation chain. A designer expresses a problem by extracting an external image from his mental model, e.g. draws a picture (externalisation). The extracted image is communicated to a worker who links the external image to his mental model (internalisation). To help the linking (internalisation), the designer must extract an external image such as will maximally fit the worker's mental model. Now the worker can express his hands-on knowledge in the form of the external image and to convey it back to the designer.

Knowledge is created in this chain: we know that a good way to understand a problem is to explain it to someone else. Other chains are also possible, but one way or another all are based on extracting, communicating and linking external images.

No knowledge management strategy can be reduced entirely to technological means.

It is no coincidence that similar concepts are exploited in public relations, for example, the 'message – communication channel – target audience' chain, as well as images and metaphors.

Virtual reality technology as a knowledge creation facilitator

It is here where advanced simulation and visualisation technologies such as virtual and augmented reality start playing a role as knowledge creation facilitators.

Virtual reality is a paradigm that enables the same means of perception of the computer-generated world (a virtual model) as the real world (the modelled object). The properties of the virtual model are obtained through interacting with it by means of virtual experiments, i.e. the virtual model must be treated in the same way as the real object that it models [20].

Because of the ability to perceive the virtual model in the same way as reality, and to engage in interaction with it, the use of virtual models helps to extract, communicate and link external images in the knowledge creation chain.

Of course, the real object or situation can be used as an external image, although this is not always feasible due to cost or real-world constraints. But when it is partially feasible to use real objects, augmented reality can be exploited to combine the real and the virtual. It is not a question of whether real is better than virtual, or vice versa: it is about flexibility. When the real object is not available, one has the choice of substituting it with a virtual model.

Virtual modelling brings all the benefits of modelling in general but, unlike traditional

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> Only virtual modelling enables accounting for the human in a non-reductionist way.

engineering modelling primarily applicable to machines, only virtual modelling enables accounting for the human in a non-reductionist way.

Research in human-machine systems

The problems that we briefly discuss in this article have been investigated in two large VTT-coordinated EU-funded research projects: ManuVAR (2009–2012) and Use-it-wisely (2013–2016).

The ManuVAR project – Manual work support throughout system lifecycle by exploiting virtual and augmented reality – focused on high-value, high-knowledge manual work that requires years of training and experience, and cannot therefore be automated or offshored.

The project covered five industry applications: terrestrial satellite assembly, design of assembly lines in small enterprises, maintenance in the railway sector, training in non-destructive techniques in power plant maintenance, and heavy machinery productisation.

A number of manual-work-related issues common to all applications were identified. The most prominent issues were problems with the bi-directional communication between various actors across the system lifecycle, poor interfaces to information systems, and inefficient knowledge management [21].

These issues were addressed by developing a virtual model as a communication mediator for all actors in the lifecycle: from workers to engineers and managers. Adaptive virtual and augmented reality user interfaces also helped to fit the complex virtual model to all actors.

The Use-it-wisely project – Innovative continuous upgrades of high investment product-services – will concentrate on systems with a long service life, such as steam turbines, rock crushers, future service spacecraft, office workplaces, heavy goods vehicles and boats.

The project is based on the human-machine-systems approach. Along the product lifecycle, actor-product-service systems are continuously formed and adapted to satisfy their changing goals and uncertain environment, by modifying system parameters, procedures, and structure.

As a result, the actor-product-service system becomes self-organised and self-regulated, employing the knowledge and skills of human actors connected by an interactive collaborative environment.

In these projects, the industry indicated considerable interest in the human-machine systems research. The research is supported by the EU2020 strategy [22], where human abilities are made fundamental to the future innovation-based society as it becomes evident that a higher intellectual effort [23] can compensate for the negative economic effect of limited basic resources and shortage of energy.

Recommendations for the future

We would like to summarise a few recommendations for a wide audience of industry top managers and policy makers:

1. Human abilities are fundamental for sustainable social and economic prosperity. Instead of battling the natural phenomenon of global offshoring or the limits of production, the industry could focus on the type of work and systems that leverage the strongest human abilities: heuristic control, skills and knowledge.

Engaging humans is key to designing human-machine systems.

2. People carry and create knowledge. Once this is recognised and people's knowledge is put to work, many societal challenges of today, such as unemployment, ageing population and shortage of natural resources, could be addressed. Furthermore, any company knowledge management strategy must rely primarily on people, and support the knowledge creation chain.

3. A human-machine system is a unity of machine and human working towards their common goal. Engaging humans is key to designing human-machine systems. Virtual and augmented reality are particularly useful in engaging the human and supporting knowledge creation.

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