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A NEW GENERATION OF PRODUCTION WITH CYBER-PHYSICAL SYSTEMS – ENABLING THE BIOLOGICAL TRANSFORMATION IN MANUFACTURING

Within 200 years since the industrial revolution manufacturing systems have often changed their faces. Emerging nations, new markets, new inventions and the changing needs of the society forced them to adapt. Until today, the arising challenges are immensely diverse: highly individualized products, decreasing manufacturing time, limited resources and critical ecological footprints are only a few of them. Oftentimes solutions for these issues and other future requirements can be found by interrogating nature. Applying knowledge of biological principles to industrial manufacturing processes is recently referred to as „biological transformation of manufacturing systems“. Hereby three levels of a biological transformation are introduced, starting from inspiration over integration to the interaction of biological and technical systems. The paper illustrates the idea of biological transformation with specific examples for each level. On the inspiration-level the design of manufacturing systems with elements of natural ecosystems is described. Thus flexibility is increased, material cycles are closed and waste will be reduced. Furthermore the integration-level is illustrated by the use of microorganisms in cutting fluids. Finally, evolutionary computing within an automatic joining cell is shown as an example for the interaction-level.

1. INTRODUCTION

In the course of history, manufacturing systems have often changed because of fundamental inventions or developing societies with new ambitious needs. Today's challenges are immensely diverse. On the one hand there are fundamental global problems, for instance the climate change, limited resources and arising nations with millions of inhabitants that increase their standards of living. The United Nations (UN) therefore defined seventeen Sustainable Development Goals (SDGs) to emphasise the fields

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of action, [1]. Because of their global economic meaning manufacturing systems play a very important role by achieving these goals.

The following SDGs are particularly related to the biological transformation, [2, 3]:

- SDG 2 Zero hunger;
- SDG 3 Good health and well-being;
- SDG 6 Clean water and sanitation;
- SDG 7 Affordable and clean energy;
- SDG 9 Industry, innovation and infrastructure;
- SDG 12 Responsible consumption and production;
- SDG 13 Climate action.

On the other hand the consumer behaviour is changing as well as can be seen in Fig. 1. When a uniform mass production was a paradigm of the last decades, nowadays highly individualised products, services and solutions in a mass production scale are demanded.

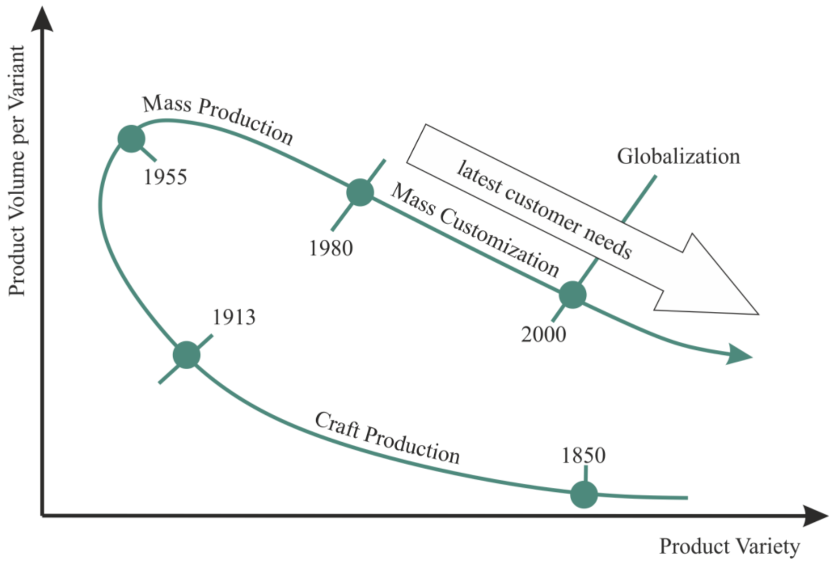

Fig. 1. The Global Manufacturing Revolution according to [4] with latest customer needs

Furthermore since the 1980s costumer needs have changed. Nowadays customers require an increasing amount of information about the products they buy and services they use. Consumers set enhanced value on environmentally friendly production, supply chains and materials as well as fair working conditions. To meet these requirements future manufacturing systems and processes have to be more flexible, highly adaptive and most of all more sustainable. Solution approaches with origin in nature and the potential to fulfil these requirements were lately summarised under the term *biological transformation of manufacturing systems*. Selected approaches closely relating to production systems and machine tools are in the focus of research at the Fraunhofer IWU and will be discussed in this paper.

Hence the paper is organized as follows: At first the term of a biological transformation is presented and subsequently three examples investigated at the Fraunhofer IWU are presented. Therein Cyber-Physical Productions Systems (CPPS) inspired by natural ecosystems as well as self-adapting processes and microorganisms in cutting fluids will be described. Finally the fundamental ideas of the paper are summarised.

2. THE BIOLOGICAL TRANSFORMATION OF MANUFACTURING SYSTEMS

With the digital transformation as one of its most important and most powerful enablers the biological transformation of manufacturing systems represents a new generation of production. It summarises a large number of different ideas and approaches in the fields of bio-economy, biomimicry, biotechnology and production systems, [3].

Many authors have introduced definitions that basically refer to the term *biologicalisation* instead of *biological transformation*, but both terms can be used synonymously. With the scope of manufacturing systems and machine tools Byrne et al. [5] defined the term *biologicalisation in manufacturing* as "The use and integration of biological and bio-inspired principles, materials, functions, structures and resources for intelligent and sustainable manufacturing technologies and systems with the aim of achieving their full potential". The publication therefore presents three main pillars of *biologicalisation* with *health, food and agriculture* as the first pillar, *environmental sustainability and energy* as the second next to the third pillar *manufacturing and material*. This illustrates the diversity of subjects and issues affected by the term *biologicalisation*.

Within this paper a shorter definition is used which specifies the biological transformation of manufacturing as "the systematic application of the knowledge of biological processes aiming at optimizing a production system", [6].

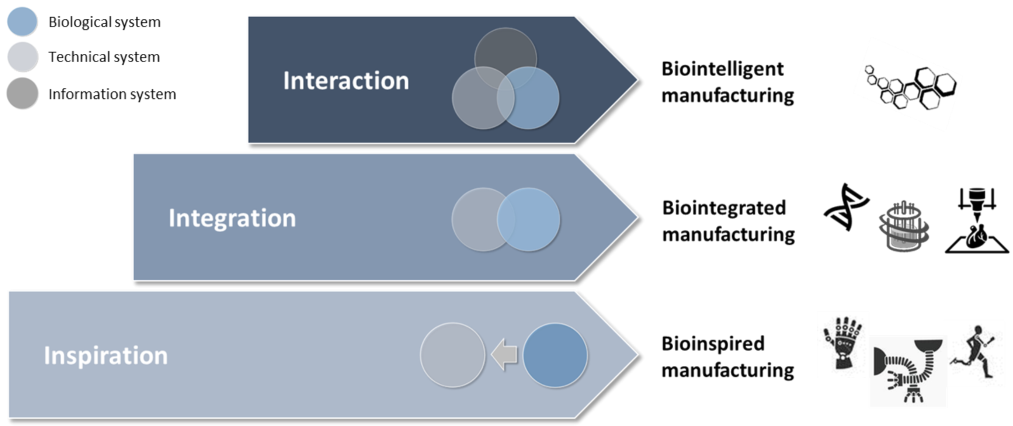

Fig. 2. The three levels of the biological transformation of manufacturing according to [6]

As can be seen in Fig. 2 three levels of a biological transformation are distinguished starting with the inspiration-level which is followed by the integration-level and the level of interaction, [6]. The levels imply how much biosphere and technosphere are merging. On the inspiration-level biological phenomena are transferred to value creation networks, [6]. Bioinspired concepts, for instance lightweight structures, are well known in technology and have been applied for years. The integration-level is a further step of development within the biological transformation of manufacturing systems. Herein biological systems are actually integrated into manufacturing systems, e.g. the substitution of chemical processes by biological processes, [6].

The last level towards a ground-breaking biological transformation of manufacturing systems is the level of interaction. It represents the final step towards a fully biointelligent value creation network which is the result of a completely new production paradigm. On the interaction-level technological, biological and information systems merge and interact with each other, [6].

Independently from the tangible definition of biological transformation it becomes continuously obvious, that manufacturing and manufacturing systems need to change both, in their focus and their appearance due to altered requirements of consumers and politics (SDGs). In the following sections, new approaches to invigorate the idea of biological transformation by the Fraunhofer IWU and partners are presented, divided up into the introduced levels.

3. INSPIRATION – CHARACTERISTICS OF NATURAL ECOSYSTEMS TRANSFERRED TO CYBER-PHYSICAL PRODUCTION SYSTEMS

On the inspiration-level biological phenomena, evolutionarily developed over millions of years, are imitated within technological systems, [6]. Next to materials and structures functionalities and organisation solutions can be transferred to production systems as well.

An example are Cyber-Physical Production Systems (CPPS) which have a similar structure compared to natural ecosystems with sub-elements, specific tasks and system behaviour and interconnection (communication, exchange of resources). Hence characteristics of natural ecosystems can be abstracted and transferred to CPPS to improve their performance and lift production to a new level concerning sustainability, robustness and flexibility.

<u>System of Systems</u>

Fundamentally CPPS base on a system of Cyber-Physical Systems (CPS) with every CPS combining mechatronics e.g. sensors and actors with software on the component level. Fig. 3 illustrates how CPS form a CPPS as system of systems in the context of Industry 4.0. Several CPS are linked and communicate with each other, with users and cloud-services. Hence in the context of production a Cyber-Physical Production System is formed which connects the communication-level with the business level in Industry 4.0. Within a CPPS several machine tools, robots and other manufacturing facilities exchange information. However a single machine tool can also be seen as a CPPS consisting of different intelligent components.

An example can be given by the controlled fluidic tempering of a machine tool frame as an intelligent machine tool component as can be seen in Fig. 4, [7]. A large number of distributed and redundant temperature sensors permanently measure the temperature of the machine frame. The behaviour of the machine frame as a result of the temperature field is simulated using a digital twin and correction values are subsequently determined by the controller. The achieved information is conveyed to intelligent pumps which cool down the machine frame. Hence the CPPS machine frame is built up by several CPS forming an intelligent machine component.

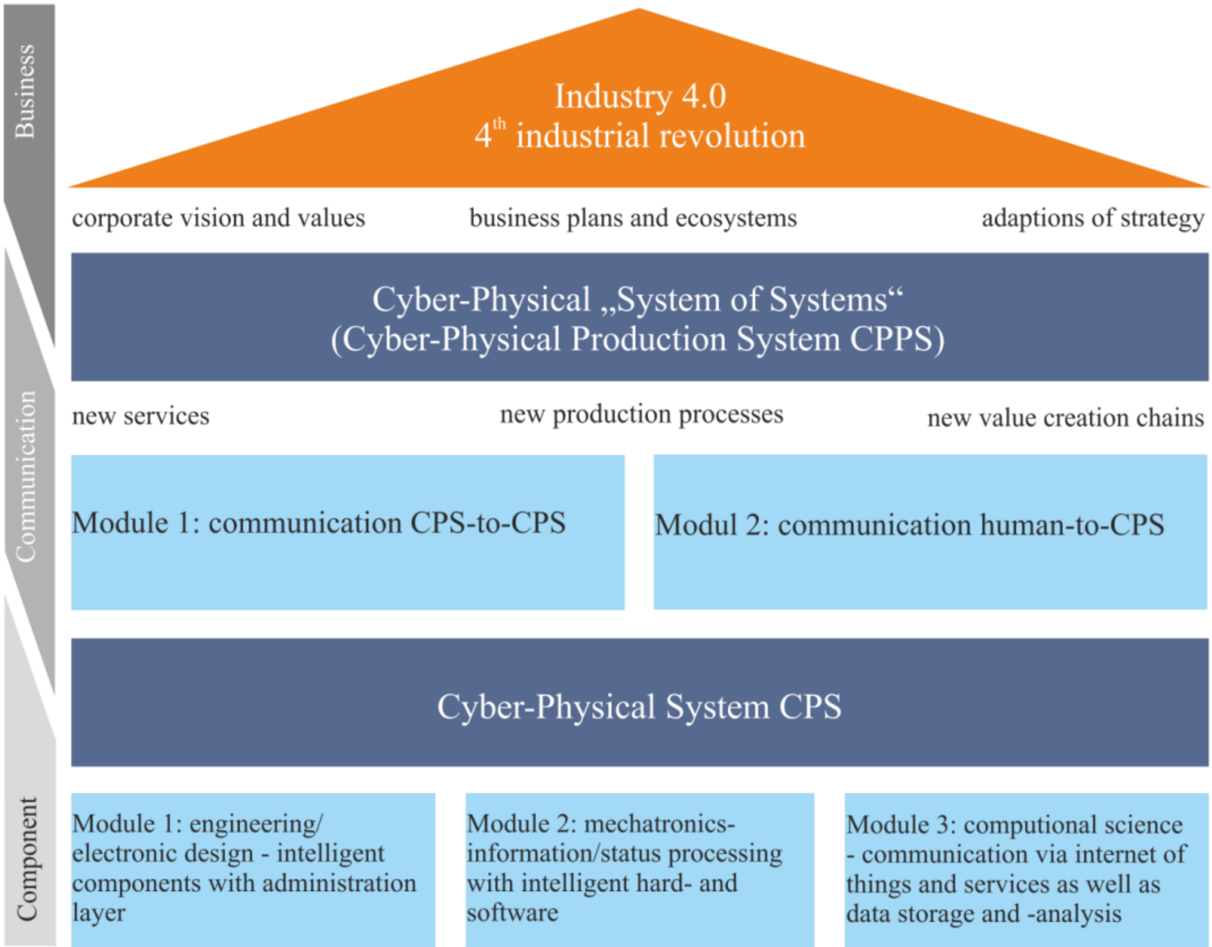

Fig. 3. CPS and CPPS in the context of the 4th industrial revolution [9]

A similar system of systems structure with a substantial degree of intelligence and communication can be found in biological systems as well. A natural ecosystem for instance is a community of individuals of different species and their not living environment, [2]. All individuals within the system have their own intelligence and can be understood as subsystems. Animals have brains and are able to think while plants have an intelligence programmed in their genes. Additionally the individuals of the same species and of different species are able to communicate with each other. Wolves for example organise their hunts by howling while plants attract insects by colours or smell.

Based on this behaviour a natural ecosystem exhibits characteristics which can be abstracted and transferred to CPPS. For instance, the complex network of relations between the participants is able to change dynamically due to variable boundary conditions.

The achieved changeability can be used in production systems to adapt the system to varying process parameters, failing machines or individual customer needs. Thus the flexibility of manufacturing systems in terms of low batch sizes, higher accuracy and reduction of process time can be increased. Furthermore by the integration of a large number of different participants a high degree of diversity is gained. As species-rich ecosystems are more robust than monocultures, the production system is more robust as well.

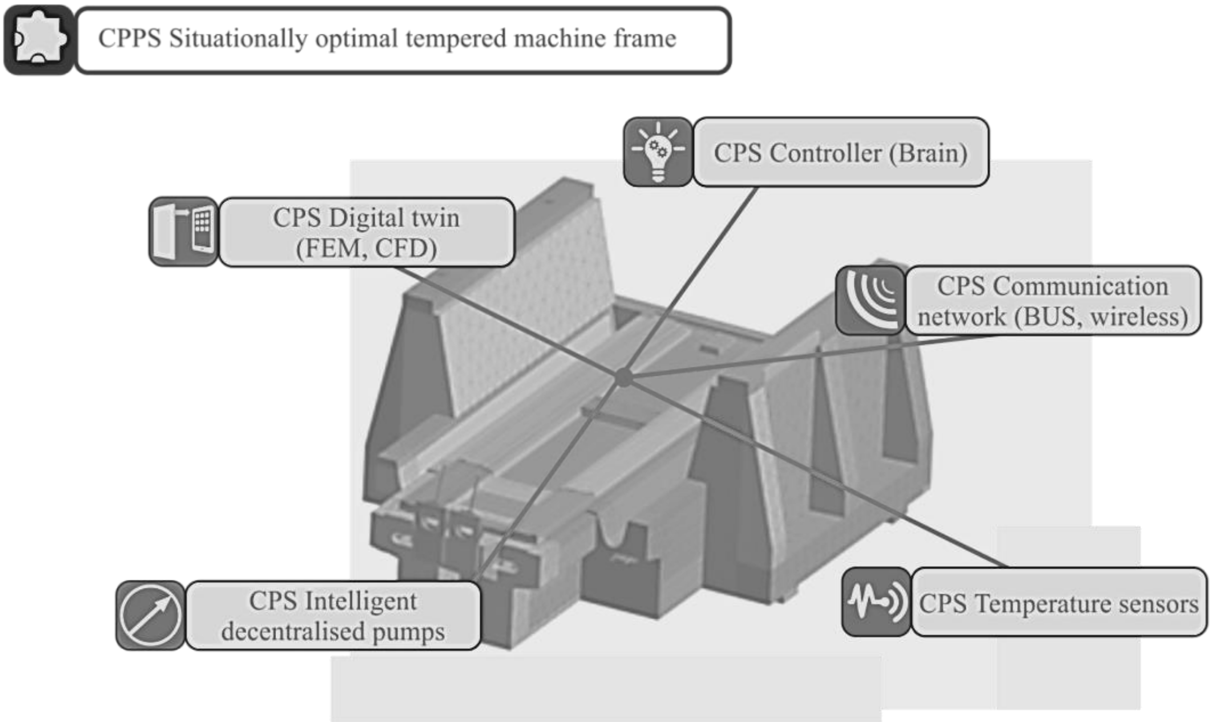

Fig. 4. Situationally optimal tempered machine frame designed as CPPS

Value creation networks

On a higher level of abstraction the CPPS-structure can be transferred to a value creation network as well. The emerging of additive manufacturing technologies for instance allows decentralised manufacturing in urban spaces (Fig. 5). The concept of urban production contains distributed production facilities as subsystems e.g. 3D printers or transport systems. The subsystems communicate with each other to convey information e.g. about available job capacities. Furthermore product data like CAD-files are transmitted via a several communication network or the internet. An intelligent transport system delivers materials, picks up the finished products or carries parts to the next process station. The entity of all these subsystems is another CPPS on the value creation level.

In summary, using naturally inspired CPPS in future manufacturing systems has several benefits. On the one hand processes can be made more efficient. Intelligent machines and components save material, energy and thus resources and therewith contribute to the aim of fulfilling the SDGs. Therefore the biological transformation will lead to a more sustainable production. Moreover waste and damage is prevented by early recognising failures and finding alternatives and thus costs and production time are reduced.

On the other hand the flexibility of the process chain is increased. Low batch sizes are possible because the CPPS adapts itself. Thus the requirements of highly individual products can be met.

The future demands on CPPS-based manufacturing systems are therefore intelligent communicating machines, the existence of exchange platforms, the utilisation of common data formats and the validation of legal issues. The Fraunhofer-Gesellschaft therefore establishes a research centre for CPPS in Dresden for further research on these fields with focus on batch size one production.

Fig. 5. Elements of an urban production, Fraunhofer-Institute for Industrial Engineering IAO

4. INTEGRATION– USING MICROORGANISMS IN CUTTING FLUIDS

The actual integration of biological systems into production systems constitutes a further level of the biological transformation. Although mankind has used this combination in manufacturing processes for hundreds of years for instance to brew beer the biological transformation offers new possibilities to merge bio- and technosphere.

The use of microorganisms in machining processes is an innovative example for the integration-level. In the current literature two approaches can be found.

Istiyanto et al. [8] and Hocheng et al. [9] showed the utilization of microorganisms for micromachining metals in their publications. They used bacteria that metabolize metal for their energy production. Thus when microorganisms are used as tools the process is referred to as biomachining according to [8].

Furthermore microorganisms can be integrated into the metal working fluids (MWF) to replace mineral-oil-containing MWFs and thus reduce the pollution of the environment. First investigations on this topic have been made by Brinksmeier and colleagues in [10]. The potential of microorganisms in MWFs is supposed to be very high, because current MWFs have to be treated as toxic waste. The volume of disposed water-based MWFs in Germany in 2014 amounts 791.000 tons according to [11]. Therefore the manufacturing costs caused by the disposal of conventional MWFs could be reduced significantly by the use of non-toxic microbial-based MWFs.

Moreover Brinksmeier et al. found additional positive effects of microbial-based MWFs on cutting processes including decreasing forces and tool wear with better surface finish, [10]. The utilisation of MWFs with microorganisms instead of conventional MWFs could therefore be more efficient and significantly save resources as well as manufacturing costs. Because of the immense potential of microbial-based MWFs the Fraunhofer Institutes for Interfacial Engineering and Biotechnology IGB and Machine Tools and Forming Technology IWU cooperate to intensify further investigations on this topic. Currently a variety of microbial-based MWF recipes are investigated concerning their applicability for cutting operations. Subsequently, a subset of the developed fluids is analysed in real cutting processes. The expectation of this basic research is to find a suitable and also cost effective fluid to replace the state-of the-art cutting fluids and to contribute to fulfilling the SDGs.

5. INTERACTION – IMPROVING AN AUTOMATED JOINING CELL WITH BIOLOGICAL PRINCIPLES

The interaction-level represents the final state of the biological transformation of manufacturing, where technological, biological and information systems interact. Hence a biointelligent value creation network is formed.

Together with other Fraunhofer Institutes the Fraunhofer IWU pursues the idea of interaction by adapting biological principles into manufacturing processes within the lighthouse project EVOLOPRO. The aims are increased productivity, more robust processes and the improvement of products. The project is based on the concept of *Biological Manufacturing Systems* (BMS) that was already defined in the 1990s with approaches of self-organisation, machine learning and evolutionary algorithms, [12]. However, back in that time this remained only a concept whereas BMS now are put into reality based on digital transformation.

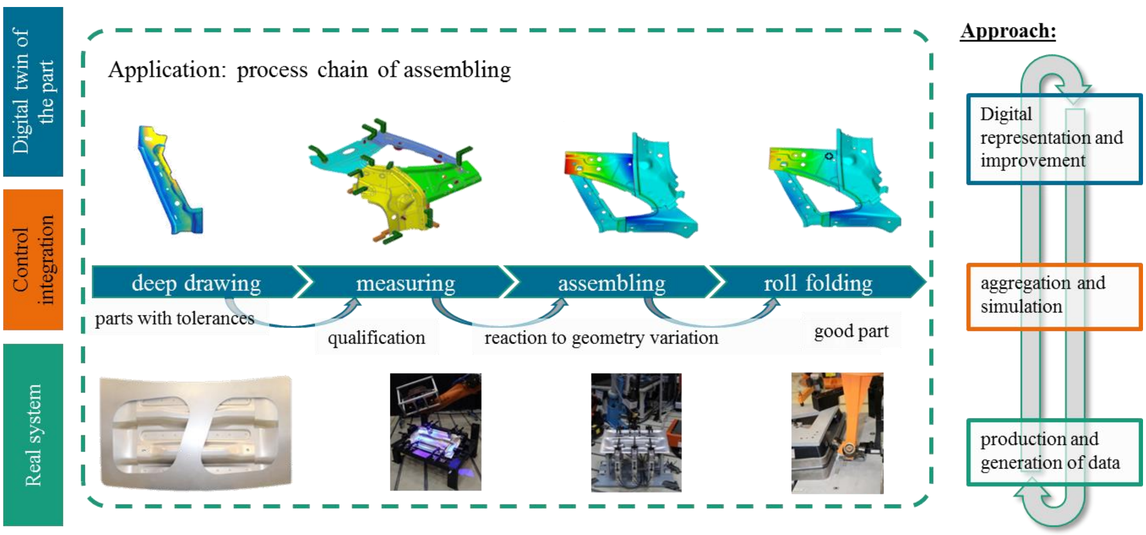

Fig. 6. Improvement of the assembling process through biological algorithms within EVOLOPRO leading to a cognitive production system [12]

The main focus of EVOLOPRO is the utilisation of the biological principles of diversity of variants and the theory of facilitated variation for complex self-adapting technological processes, [12]. Therefore the latest research results in the fields of molecular, developmental and evolutionary biology are transferred to algorithm-based production systems, [12]. In this context the approach of self-adapting manufacturing processes is mainly based on machine learning and artificial intelligence (AI). Previously three enablers are identified and utilised to implement self-adapting processes: the digital twin, the digital environment and mechanisms of facilitated variation translated into algorithms for manufacturing issues. In this case the digital twin functions as a virtual copy of each product that contains information about design, changes of state and their causation during the whole lifetime of the product. The entity of all digital twins represents a gene pool with further information about correlations and added simulations. In contrast to the digital twin the digital environment contains all relevant requirements faced by the product to estimate the fitness of each individual twin. Finally, to gain self-adapting products and processes the mechanisms of facilitating variation are transferred to algorithms for manufacturing systems.

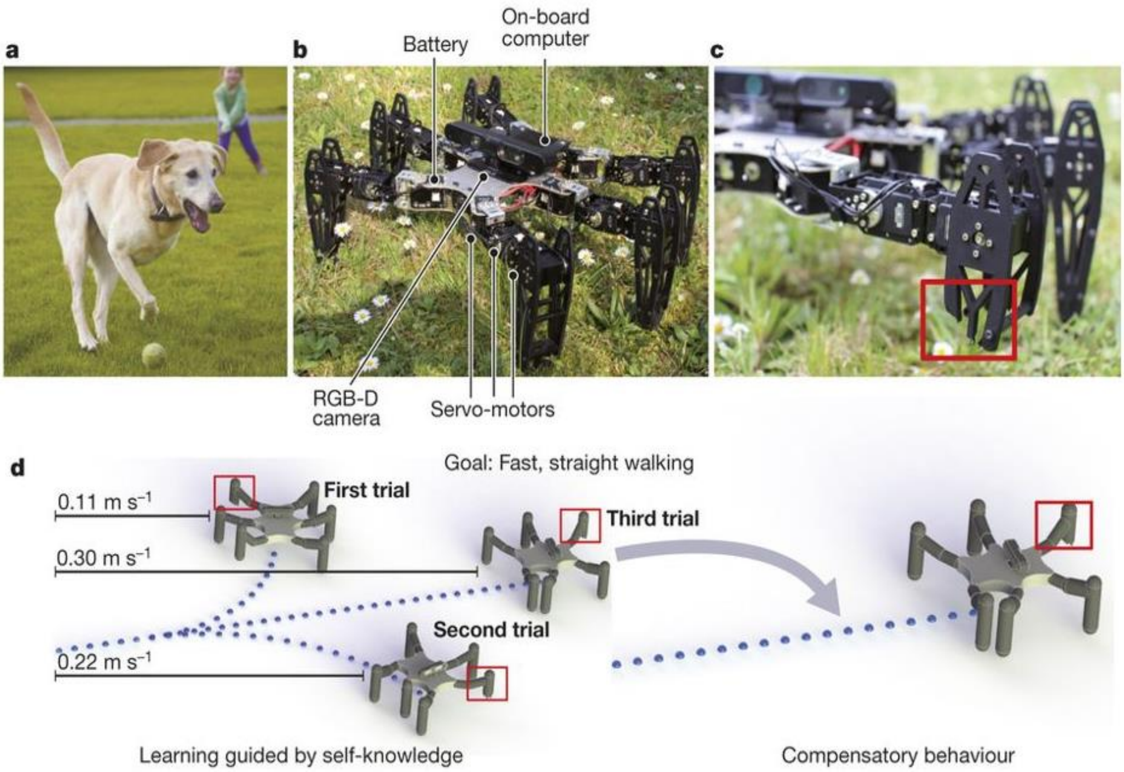

Fig. 7. a) A dog relearns to run with three legs, b) Undamaged hexapod robot, c) A possible damage of the hexapod robot, d) Hexapod robot learns to walk with five legs [13]

The results of research will be applied to suitable test-cases. Together with the Fraunhofer Institute for Material and Beam Technology IWS an automated joining cell for assembling car-body parts is taken into account [12]. By means of a self-adapting manufacturing process the commissioning phase will be shortened by auto-adaptive adjustment of support surfaces. Also the wear of the folding jaw as a main influence factor for the clinching process will be considered to adjust for better manufacturing quality. The multiplicity of measures, such as enhanced communication, digital part representation, data fusion and biologically inspired facilitated variation leads to a cognitive production system.

As a new aspect a non-linear improvement of the production process permits steps within the development. Thus similarly continuing developing paths are possible and improvements need not to be done multiple times. Moreover alternative optima can be found like a dog is able to relearn how to run with three legs when one leg is missing (Fig. 7), [13]. This can be achieved by algorithms of the facilitated variation. Applying them to production system e.g. joining cells offers completely new approaches of improvement.

6. CONCLUSION

The biological transformation of manufacturing systems is a holistic concept of future manufacturing systems that includes approaches of biomimicry, biotechnology, bioeconomy and other far-reaching domains. It provides solutions for global challenges like changing climate, the reduction of ecological footprints, resource scarcity and the improvement of living conditions all over the world, [3].

A definition of the biological transformation is given as “the systematic application of the knowledge of biological processes aiming at optimizing a production system” [6].

Based on this definition the three levels inspiration, integration and interaction are introduced. Selected examples which are investigated at the Fraunhofer IWU have been described in detail.

Characteristics of natural ecosystems are imitated within Cyber-Physical Production Systems to increase the flexibility and the robustness of the system and makes production more sustainable. Furthermore the utilization of microorganisms in cutting fluids illustrates the integration of biological systems into technological systems. The final level of interaction is pursued within the lighthouse project EVOLOPRO to merge technological, biological and information systems.

Due to the large potential to meet future global challenges the biological transformation of manufacturing systems is intensely explored within the Fraunhofer-Gesellschaft. The selected examples are in the focus of research at the Fraunhofer Institute of Machine Tools and Forming Technology IWU in cooperation with other Fraunhofer Institutes and partners.

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